Prototype of Analog Feedback Communication System: First Results of Experimental Study

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***Abstract*—The paper presents first results of an experimental study of narrow band optimal analog adaptive feedback communication system (AFCS) designed for analog signals transmission. The prototype system implemented optimal transmission – reception algorithm derived and studied in [1]-[4] and other author's works. The aim of the study was a comparison of theoretically expected performance of the system (limit accuracy, power and bandwidth efficiency of transmission) and performance provided by its hardware implementation.**

***Keywords*—analog transmission, adaptive modulation, AFCS, hardware implementation, design, limit energy-power efficiency, testing**

I. INTRODUCTION

In the years 1960-1970s, analog transmission was the subject of intensive wide scale research. All the obtained results (e.g. [5],[6]) proved a capability of analog CS with feedback channels (AFCS) to transmit signals without coding with minimal mean square error (MSE) and bit rate equal to the capacity of the forward channel. However, years of work gave no practical results and, in the middle of 70th, interest of researchers in AFCS theory practically disappeared and their attention was redirected to the development of digital CS.

Analysis of publications in AFCS theory had shown that the only reason which made excellent and clear results not implementable was omission of saturation caused by always limited output range of the forward transmitters. Even rare cases of saturation cause the effect similar to the appearance of large bit error rate (BER) in digital CS. Solution of the problem (see Sect II, also [1]-[4]) enabled derivation of transmission–reception algorithm which, in turn, enabled a design of optimal AFCS operating at the information limits. In the current paper, this algorithm was used as analytical basis for design of the hardware prototype of optimal AFCS.

The paper gives a brief description of the prototype operation, methods of its performance measurement and results of initial series of experiments.

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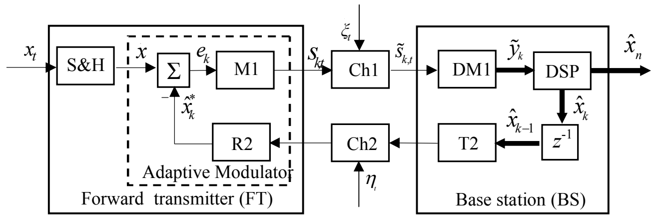

Fig. 1. Block diagram of AFCS

II. BASIC IDEA OF AFCS TRANSMISSION

The block diagram of AFCS is presented in Fig. 1. Full description of the system functioning is given in [1]-[4], and only main details of AFCS transmission are discussed below.

The input signal x_t is sampled in S&H unit. Each sample is held at the first input of saturating unit Σ till the end of its transmission The main idea of AFCS transmission consists in the cyclic (iterative) transmission of not the input sample, but of the error of its estimate $\hat{x}_{k-1}$ computed in digital signal processing (DSP) unit of base station (BS) in previous cycle ($k=1,...,n$). This estimate is delivered to the receiver R2 of forward transmitter (FT) over digital feedback channel: transmitter T2-channel Ch2-receiver R2 and is routed to the second input of the saturating unit Σ. The feedback noise η_t distorts the received estimate, and signal routed by the receiver R2 to Σ has the value $\hat{x}^*_{k-1}=\hat{x}_{k-1}+\nu_k$ where ν_k is the transmission error. Subtractor Σ forms a difference signal $e_k = x - \hat{x}_{k-1}+\nu_k$ and routes it to the input of the adjusted analog modulator M1.

It is assumed the modulation index of AM modulator M1 can be set, in each cycle of the sample transmission, to the required value M_k. Omitting high frequency components, signals emitted by the forward transmitter and received by BS can be written, respectively, in the form:

$$s_{t,k} = A_0 M_k e_k = A_0 M_k (x - \hat{x}_{k-1} + \nu_k), \qquad (1)$$

$$\tilde{s}_{t,k} = A_0 \frac{\gamma}{r} M_k e_k + \xi_k = A M_k (x - \hat{x}_{k-1} + \nu_k) + \xi_t \quad (2)$$

where A_0 is maximum value of the emitted signal, and violation of the condition $|M_k e_k| \le 1$ causes saturation of the transmitter. Value γ describes the channel gain, r is the distance between FT and BS, and $A = A_0\gamma / r$. The mean value x_0 and variance σ_0^2 of the input signals are assumed to be known. The channel noise ξ_t is additive white Gaussian noise (AWGN) with double side power density $N_\xi / 2$. Feedback errors ν_k are considered as AWGN with the variance σ_ν^2.

Transmission of estimation errors e_k creates a new quality: these errors monotonically diminish in sequential cycles that permits to increase corresponding values of M_k. The greater M_k, the greater signal-to-noise ratio (SNR) at the channel Ch1 output. This improves the accuracy of recovering the estimation errors e_k in BS and, as result, accuracy of estimates of the sample formed by DSP unit according to the equation:

$$\hat{x}_k = \hat{x}_{k-1} + L_k \tilde{y}_k, \ (\hat{x}_0 = x_0) \tag{3}$$

where x_0 is the mean value of normally distributed input signals (variance of the signals σ_0^2 is assumed to be known), and $\tilde{y}_k$ are the signals at the demodulator DM1 output:

$$\tilde{y}_k = AM_k e_k + \xi_k = A_0 \frac{\gamma}{r} M_k e_k + \xi_k . \tag{4}$$

In turn, parameters L_k in (3) are set to the values additionally minimizing mean square error (MSE) of the estimates $\hat{x}_k$.

The presented communication scheme is close to these considered in [5]-[6]. It determines the structure and parameters of optimal AFCS which may transmit the samples with minimal MSE of estimates $P_k = \mathrm{E}[(x - \hat{x}_k)^2]$. As it was shown in [1]-[4], for $\sigma_\nu^2 << \sigma_0^2$, optimal AFCS transmits the samples with minimal MSE, and saturations of the forward transmitter FT will be eliminated with a probability μ if, in each cycle, parameters M_k and L_k are set to the values:

$$M_k = \frac{1}{\alpha\sqrt{P_{k-1}^{\min}}} \ ; \ \ L_k = \frac{1}{AM_k}\left(1 - \frac{P_k}{P_{k-1}^{\min}}\right) \tag{5}$$

where $P_k^{\min}$ are minimal values of corresponding MSE of estimates $\hat{x}_k$ determined by the relationship:

$$P_k^{\min} = \sigma_0^2 (1 + Q^2)^{-k} . \tag{6}$$

Value $Q^2 = (A / \alpha\sigma_\xi)^2$ in (6) is signal-to-noise ratio (SNR) at the DM1 output, saturation factor $\alpha = a(\mu)$ is determined from the equation $\mu = 1 - 2\Phi(\alpha)$, where $\Phi(\alpha)$ is tabularised Gaussian integral. Power σ_ξ^2 of the noise ξ_t in the allotted bandwidth $2F_0$ has the value $\sigma_\xi^2 = N_\xi F_0$. The considered communication scheme was used as analytical basis for designing the hardware prototype of optimal AFCS.

III. Main Effects Appearing in Optimal AFCS

In [1]-[4], it was shown that optimal AFCS transmit the signals not only with minimal MSE, but bit rate and power-bandwidth efficiency of transmission also attains theoretical limits. Moreover, it was established a difference between the capacities of the forward channel and AFCS as a whole (as a generalized communication channel). Namely:

- The bit rate R_k^{Ch1} of transmission over forward channel does not depend on the number of cycles and is equal to the capacity of the channel (Shannon's formula):

$$R_k^{Ch1} = C = \frac{1}{2}\log_2(1+Q^2) = F_0 \ \log_2\left(1 + \frac{W_{\max}^{Ch1}}{N_\xi F_0}\right) \ \text{[bit/s]} \tag{7}$$

where $W_{max}^{Ch1} = (A_0\gamma / \alpha r)^2$ is the mean power of the signal at the channel Ch1 output.

- The bit rate R_n^{AFCS} at the optimal AFCS output is equal to the capacity C_n^{AFCS} of the system [1]-[4] that is:

$$R_n^{AFCS} = C_n^{AFCS} = \frac{F_0}{n}\log_2 \frac{\sigma_0^2}{P_n^{\min}} \ \text{[bit/s]} \tag{8}$$

Formulas (7), (8) determine corresponding bandwidth efficiencies of transmission R_k^{Ch1} / F_0 and C^{AFCS} / F_0

- The power efficiencies for the channel Ch1 and AFCS attain the limit values determined by the expressions:

$$\frac{E^{bit}}{N_\xi} = \frac{F_0}{C}\left(2^{\frac{C}{F_0}} - 1\right) = \frac{Q^2}{\log_2(1+Q^2)} \ , \tag{9}$$

$$\frac{E_n^{bit\ AFCS}}{N_\xi} = \frac{nQ^2}{\log_2 \frac{\sigma_0^2}{P_n^{\min}}} = \frac{F_0 Q^2}{C_n^{AFCS}} \ .; \ \ Q^2 = 2^{\frac{C_n^{AFCS}}{F_0}} - 1 . \tag{10}$$

- The capacities and power efficiencies of the channel Ch1 and AFCS coincide, if $P_n^{\min} \geq \sigma_\nu^2$. For $P_n^{\min} < \sigma_\nu^2$ formulas (7), (11) remain valid but (8), (10) change the form [1]-[4].

IV. Experiments with Prototype of Optimal AFCS

The goal of the first series of experiments with prototype was measurement of the power and bandwidth efficiencies of transmission and verifying the effects predicted theoretically (partially described in Sect. III). The main measured characteristic was a dependence of the MSE of transmission on the number of transmission cycles at different distances between the forward transmitter and base station. Experiments were carried out inside the faculty building. Testing sequences of $M = 100$ random pulses (samples) $x^{(m)}$, $m = 1,...,M$, were generated using identical sequences of codes stored in the controllers of FT and BS. Each sample was transmitted in 15 cycles. In each k-th cycle, controller of BS computed corresponding estimate $\hat{x}_k^{(m)}$ and routed to the memory unit and to the transmitter of feedback channel. After transmission of the last sample, formed set of estimates $\hat{x}_k^{(m)}$ ($m = 1,...,M$, $k = 1,...,15$) was used for computing the MSE of transmission in consecutive cycles. Computation was realized by the BS controller according to the formula:

$$\hat{P}_k = \frac{1}{M}\sum_{m=1}^{M}[x^{(m)} - \hat{x}_k^{(m)}]^2 . \tag{12}$$

The results of indoor measurement of MSE of transmission (in dB) on the distances 40, 50, 75 m. are presented in Fig. 4:

$$\mathrm{MSE}_k[\mathrm{dB}] = 10\log_{10}\left(\frac{\hat{P}_k}{\sigma_0^2}\right). \tag{13}$$

The plots show practically linear diminution of $\mathrm{MSE}_k[\mathrm{dB}]$ w.r.t. the number of cycles. Non-linear deviations could be created by non-stationary noise emitted by electronic devices in neighbor laboratories, what deserves some deeper analysis.

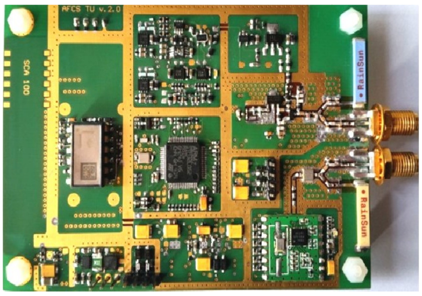

Fig. 2. PCB module of forward transmitter.

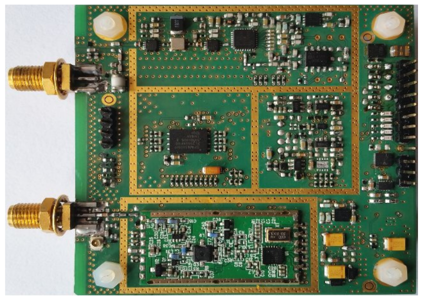

Fig. 3. PCB module of base station.

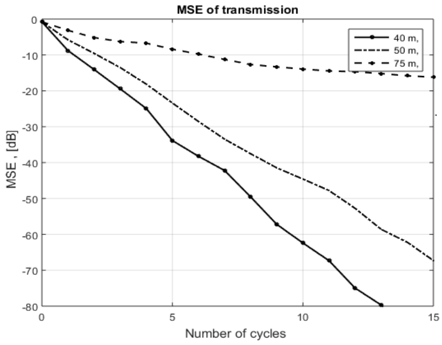

Fig. 4. Changes of MSE in sequential cycles of the samples.

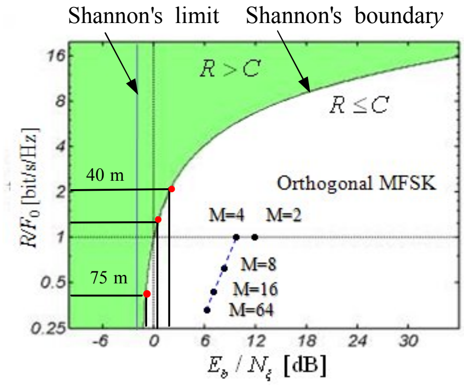

Fig. 5. Measured values of P-B efficiency of prototype.

Analysis of the plots permits to conclude:

- The measured values P_k decreases exponentially i.e. according to formula (6). This proves that the developed prototype of AFCS operates in optimal mode, and presented plots describe the changes of minimal MSE attainable in corresponding experiments.
- Feedback channel noise does not influence the accuracy of transmission. The reliable data transfer abruptly ceased at the distances greater than 75 meters due to saturation of decoder of the feedback channel.

The plots in Fig.4 enable numerical evaluation of the power – bandwidth (P-B)_ efficiencies of transmission. The bandwidth (B-) efficiency of AFCS can be calculated using following from (8),(13) formula:

$$\frac{C_n^{AFCS}}{F_0} = \frac{3.32}{n}\log_{10}\frac{\sigma_0^2}{\hat{P}_n} = -\frac{0.332}{n}\mathrm{MSE}_n[\mathrm{dB}] \qquad (14)$$

and power (P-) efficiency $E_n^{bit\ AFCS} / N_\xi$ [dB] can be assessed substituting the computed values (14) to formula (10). The processed results of experiments are given in Tab. 1.

In Fig. 5, computed values (red points) lay directly on the Shannon's boundary independently from scenario (distance of transmission) and draw to Shannon's limit $E_n^{bit\ AFCS} / N_\xi = -1.6\ \mathrm{dB}$ for greater distances. The latter shows that optimal AFCS may provide "ideal" transmission of signals employing transmitters of lesser power than currently used. This effect can be used for designing of high efficient low power self adjusting wireless sensors and requires further investigation.

TABLE 1. INFORMATION CHARACTERISTICS OF PROTOTYPE.

Distance (m)	40	50	75
MSE_n[dB]/n	- 6.2	- 4.4	-1.4
C^{syst} / F_0	2.05	1.4	0.46
$E_n^{bit\ syst} / N_\xi$	1.54	1.2	0.82
$E_n^{bit\ syst} / N_\xi$ [dB]	1.85	0.8	- 0.87

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