Chapter

Perfect Signal Transmission Using Adaptive Modulation and Feedback

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Abstract

The research results show that adaptive adjusting of modulators over feedback enables development of the "perfect" communication system (CS) transmitting analog and digital signals in real-time without coding with a bit rate equal to the forward channel capacity and limit energy spectral efficiency. These and other feasibilities unattainable for known CS are the result of transition from the direct transmission of samples of the input signal to the transmission of sequences of their estimation errors cyclically formed at the input of forward transmitter (FT) modulator. Each transmitted error is formed as a difference between the value of input sample and its current estimate computed in the receiver in previous cycle and delivered to FT over feedback. Growing accuracy of estimates decreases estimation errors and permits their transmission permanently increasing the modulation index and maximizing the amount of information delivered to the receiver. Unlike CS with coding, adaptive feedback CS (AFCS) can be optimized using Bayesian estimation and information theory. Absence of coders simplifies the construction of FT and reduces their energy consumption and cost. Moreover, adaptive properties of AFCS permit to maintain the perfect mode of transmission in every scenario of application. The chapter presents analytical backgrounds, experiments results and research genesis including the reasons for absence of AFCS in modern communications.

Keywords: wireless, adaptive modulation, feedback, Bayesian optimization, perfect transmission, limit energy-spectral efficiency, channel capacity, Shannon's limits

1. Introduction

The publication of Shannon's fundamental works [1, 2] coincided with the appearance of the first computers and urgent need for the development of fast and reliable channels for digital data transmission. Shannon's theory led to the almost immediate development of backgrounds of the coding and digital CS theory. The parallel fast development of high-resolution AD-DA converters and digital technologies made digitizing and coding the basic principle of signal transmission.

The side effect of the successes of digital CS was initial lack of interest in CS with feedback channels (FCS) and codeless signals transmission, although this possibility was noted by Shannon in [1, 2]. The first work of Elias [3] in this direction was published seven years later, in 1956. The results of the work showed that ideal feedback channel and proper setting of the modulation gains permit to transmit analog signals without coding in real time with the limit bit rate equal to the capacity of the forward channel—the result unfeasible in digital CS with coding. Moreover, the absence of coders radically simplified the construction of FCS transmitters. Initially not noticed, this work initiated a great cycle of research in the optimization of FCS (see e.g. [4–13]) carried out in 1960s in MIT, Bell Lab., Stanford University, NASA, and other research centres. The results of these investigations unambiguously confirmed that modulation and feedback enable a development of simple CS transmitting signals and short codes in real time perfectly and with minimal distortion. Moreover, analytical results of the research determined a way to design of the perfect FCS design.

However, since the mid-1970s, interest in the research in the FCS theory sharply declined, and, during subsequent decades, only a small number of academic papers were published. The main reason was the lack of practical results, as well as a pessimistic evaluation of the entire direction of research ("The subject itself seems to be a burned out case" [14], p. 324). It is worth adding that, at that time, short-range transmission was provided by wires, and there was no special need in wireless FCS. At the same time, development of digital technologies, communications and automatics generated a lot of complex theoretical tasks, and the industry required specialists. As a result, most FCS researchers took up these tasks.

The situation changed with the appearance of mobile communications and wireless networks (WN) containing a great number of wireless end nodes (EN), each communicating with the base station (BSt) over forward and feedback channels. This renewed interest in FCS was still, however, strictly academic [15] and without any practical results. Having no alternative, currently, all the channels of WN employ only the coding principle of transmission.

Apart from the traditional requirements for CS (maximal rate, quality, reliability, range of transmission, etc.), battery-supplied or battery-less low-power transmitters of EN should be minimally complex and minimally energy-consuming, and should satisfy a large number of the other, sufficiently rigorous requirements [16] such as maximal energy efficiency of transmission, optimal utilization of the channel bandwidth, reduction of inter-channel interference, security of transmission, and others. The set of these characteristics is now defined by the general term "performance," and the main task of designers is the improvement of the systems or channels' performance.

The development of the first generations of WN and corresponding FT did not cause any particular difficulties, but each subsequent generation does pose new, increasingly complex problems. One should stress that the performance of the lower, physical (PHY) layer channels EN-BSt dramatically influences the performance of the overall network regardless of the particularities of the higher layers' organization.

The design of the PHY layer channels is carried out almost independently from that of the higher layers and software of WN, and requires thorough knowledge of mathematics, signals processing, communication and information theory, and so on. Nevertheless, even among experienced designers, "the task of changing from a cable to wireless is still seen as a daunting prospect; wireless retains its reputation of being close to black magic. For most designers, it is an area where they have very little ability to change anything, other than the output power" [16]. A similar sentiment is expressed in [17].

This is not an isolated opinion. A large number of recent publications question the capability of the modern theory to provide any noticeable improvement in wireless transmission: "Shannon limit is now routinely being approached within 1 dB on AWGN channels ... So is coding theory finally dead? ... there is little more to be gained in terms of performance [18]"; "Whether research at the physical layer of networks is still relevant to the field of wireless communications? … any improvements are expected to be marginal [19].” Similar evaluations of the state of theory can be found in [20–22] and other works.

Analysis of the sources of problems showed that the main reason is the lack of efficient theoretical basis permitting one to investigate the behavior of wireless CS in different scenarios and to choose the versions best suited to the goals of the project.

In the following sections of the chapter, we discuss these problems and their solution. To simplify the discussion, apart from CS and FCS, we use the following abbreviations: CSC—communication system with coding and AFCS—adaptive feedback communication system transmitting signals over the forward channels (FT) using analog modulators (AMs) adjusted by the controls formed in BSt and delivered to FT over feedback channels.

2. Sources of difficulties in improvement of short-range CS performance

Let us clarify the subject of discussion. The term “performance”, relatively new in communications, is broader than the term “quality”. Furthermore, the evaluation of CS performance has its own groups of the criteria used to compare the systems by their general utility characteristics, further called the “performance” criteria. Another, relatively narrow and stable group of “analytical” criteria is used in the research as a tool permitting to improve one or a part of the performance criteria.

2.1 Basic performance criteria

The performance criteria determine the required, desired, or real characteristics of the future or existing wireless CS permitting to use these systems for solution of definite tasks in the given conditions, and to evaluate the corresponding benefits, costs, and risks [16]. The main criteria of this group are:

- range of reliable transmission
- data rate and throughput
- latency
- frequency range and channel bandwidth
- power and energy consumption
- security of transmission
- interference and coexistence
- resistance to industrial disturbances and changes in the environment
- possibility of supplying from renewable energy sources
- design, production, and deployment costs
- size, weight, price, and other characteristics.

These criteria are used for elaboration of standards and have no analytical tools for a prior evaluation of performance. Instead, each of the listed criteria has a fixed numerical evaluation determining the corresponding requirement to CS. Each standard defines a class of CS with a unique combination of performance criterions granting these systems the ability to solve definite tasks under definite conditions better than other systems. For a new system to have better performance, it should pass a certification which confirms the existence of new qualities. Moreover, to become the standard, it should be manufactured at least by three independent firms [16].

Analytical criteria serve a different purpose, and are used to establish conditions that allow the rate, quality, reliability of transmission, and other characteristics of CS to approach their limit or given values in different conditions and under given constraints. These criterions are built on adequate mathematical models of the main components of CS or of the system as a whole, and their values depend on all the basic factors influencing the work of the system. Some of these factors can be regulated by designers who search for their combination that either maximizes the "main" criterion (e.g. the rate of transmission) or minimizes its value (e.g., transmission errors) taking into account existing limitations. The results of research determine the approach to design the best system in a given class under given conditions and limitations.

Analytical evaluations of the quality of transmission are not used in performance criteria but the research results create a rigorous basis for the design of more efficient CSs and for their emergence within new standards. Nevertheless, RF (radio frequency) design "is typically the smallest section of any wireless standard" and "the hardware definition may be less than 5% of the total specification in terms of the number of pages ([16], p. 20).

Currently, the term "improvement of performance" is widely used in communications and pushed out also not strictly defined earlier term "improvement of quality" of the systems, channels, transmission, etc. In this chapter, we use both these terms. It is worth adding that the term "perfect" should be taken literally: the performance of the AFCS discussed below does attain the limits established by information theory. Note that this discussion clarifies not only the terminology, but also the relations between different groups of criteria mutually connected through plural tradeoffs. The analytical results presented below allow for the simultaneous improvement of several performance criteria (to which we will return in the final discussion).

2.2 Basic analytical criteria

Nowadays, commonly used analytical criteria in CSC performance include the bit rate [bits/s], energy [J/bit], and spectral [bit/s/Hz] efficiencies of transmission, as well as bit error rate (BER). Sets of possible values of energy-spectral efficiencies have upper bounds, and the task of designers is to make the characteristics of the system approach these boundaries under possibly smaller BER. As the basic references, the theory employs limit values of bit rate and efficiencies of the transmission usually computed for linear memory less channels with additive white Gaussian noise (AWGN). So, limit bit rate determines the capacity of the channel (Shannon's formula) as follows:

$$C = F_0 \log_2\left(1 + \frac{W^{sign}}{N_\xi F_0}\right) = F_0 \log_2\left(1 + Q^2\right), \tag{1}$$

where W^{sign} is the power of signal at the channel output, $N_\xi/2$ is the double-side spectral power density of AWGN, $2F_0$is the channel bandwidth, and:

$$Q^2 = \frac{W^{sign}}{\sigma_\xi^2} = \frac{W^{sign}}{N_\xi F_0} = SNR^{Ch}, \tag{2}$$

is the signal-to-noise ratio (SNR) at the channel output.

The energy efficiency of transmission ("energy per bit") $E^{bit} = W^{sign} T^{bit} = W^{sign}/C$ [J/bit] is determined as the energy necessary for transmission of a single bit of information with a bit rate equal to the capacity of the channel ($T^{bit} = 1/2C$ is the time of transmission).

The spectral (or bandwidth) efficiency C/F_0 describes a number of bits transmitted per second per 1 Hz of the channel bandwidth. The limit values of energy-spectral efficiencies and SNR are connected by the relationships [23–25]:

$$\frac{E^{bit}}{N_\xi} = \frac{F_0}{C}\left(2^{\frac{C}{F_0}} - 1\right) = \frac{Q^2}{\log_2\left(1+Q^2\right)}. \tag{3}$$

This formula directly follows from (1) and (2) and is convenient for practical applications. Another frequently used but less convenient measure of energy efficiency is defined as C/W_0 [bit/s/W], where W_0 is the power of transmitter.

The example of the expression for the BER computed for two orthogonal signals transmitting particular bits over channels with AWGN has the form:

$$\text{BER} = \Pr^{bit} = 1 - 2\Phi\left(\sqrt{\frac{E^{bit}}{N_\xi}}\right), \tag{4}$$

where $\Phi(x)$ is the tabulated Gaussian integral:

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^x \exp\left(\frac{z^2}{2}\right) dz. \tag{5}$$

These relationships are mutually connected by multiple tradeoffs: power-bandwidth tradeoff; tradeoffs between BER and energy efficiency, deployment efficiency-energy efficiency, and many others (see, e.g. [23, 26]). In these conditions, the development of a regular approach for the optimization of CSC is practically impossible.

The sources of difficulties are:

i. Impossibility to find, among the infinite set of possible codes, the code minimizing errors of transmission: "The existence of optimal encoding and decoding methods is proved, but there are no methods indicated for the construction or technical realization of these results [27]."

ii. Impossibility to formulate any expressions for current (not only limit) bit rate and energy-spectral efficiencies.

iii. Both the quality of transmission and the results of CSC optimization directly depend on the scenario of the system application (placement of the system, characteristics of the environment, fading, noise, path loss, etc.). Implementation of theoretical results is only possible if there is a possibility of at least partial channels identification but a system optimal in one scenario will not be optimal in another.

iv. The lack of the regular analytical approach to optimization of CSC makes impossible evaluation of the potentially achievable bounds of transmission quality and the search for the most efficient technical solution permitting their achievement.

There are many approaches for the improvement of CSC (e.g., [28–30]) but their discussion is beyond the scope of the chapter. We will note the fact stressed in the literature (e.g., in [31, 32]): theoretical bounds determined by the existent methods of analysis are unachievable for real systems. As a result, modern CSCs transmit signals with the necessary performance but nobody can assess the efficiency of their energy, spectral, and other resources utilization. The listed reasons, including scenario-dependent performance, make the development of the perfect CSCs optimally and fully utilizing their energy and spectral resources an unrealistic task.

In the next section, we show that modulation and feedback resolve the listed problems and enable elaboration of the FCS transmitting signals perfectly, as well as permit to improve their performance criteria.

3. Perfect FCS: transmission using feedback and adaptive modulation

3.1 General principles of FCS transmission

The novelty of the topic makes us begin by considering sufficiently general but not complex systems to simplify the explanation of the main ideas, mathematical tools, methods, and results. Below we consider point-to-point FCS (block diagram in **Figure 1**) assuming that the input signals are Gaussian and channel noises are AWGN, and high quality feedback channel delivers signals from the BSt to the FT with negligibly small errors. One may add that this block diagram, with different formulations of the tasks, was the subject of both early and later research in this field. The material below does not repeat any of these works but summarizes and clarifies their main ideas, approaches to problem-solving, and results to elucidate the difficulties, which had blocked the development of the theory. We also hope that the reader might appreciate the beauty of these works, which came so close to success, but which are now almost forgotten.

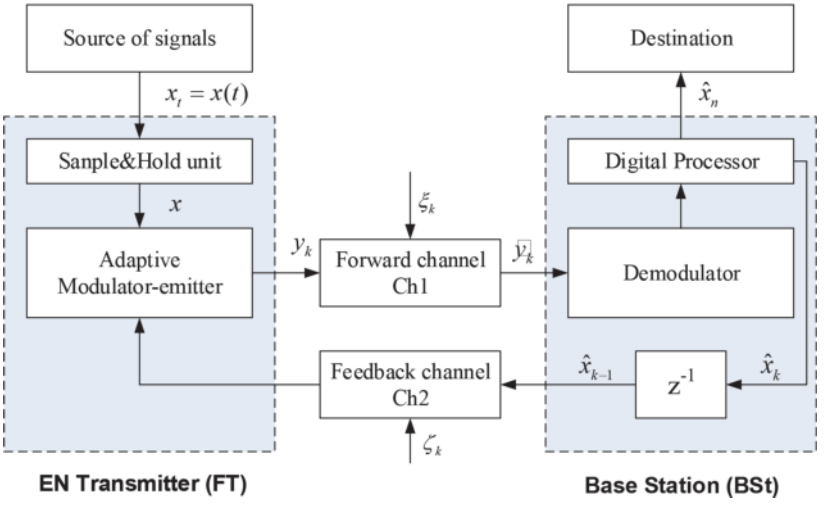

Figure 1.
General block diagrams of point-to-point AFCS.

The analysis that follows is carried out in discrete time. Samples $x^{(m)}$, $m = 1, 2, \ldots$ of Gaussian input signal x_t are transmitted iteratively, each in n cycles, and independently from previous samples. This permits to reduce the analysis of FCS functioning to transmission of a single sample x omitting the upper indices "m." The mean value x_0 and variance σ_0^2 of the samples are assumed to be known. We also assume that the feedback channel Ch2 is realized on high-quality digital components, and that influence of the channel noise on feedback transmission can be neglected. The physical forward channel Ch1 is stationary, memoryless, and its noise ξ_k, $k = 1, \ldots, n$, is AWGN with a double-side spectral power density $N_\xi/2$.

Values x of the transmitted sample are held at the input of the sample and hold unit (S&H) during the time $T_n = n\Delta t_0$ sufficient for the transmission of the sample in n cycles (T_n does not exceed the sampling period $T = 1/2F$; Δt_0 is the duration of the cycle and determines the minimal bandwidth $2F_0 = 1/\Delta t_0$ of the forward and feedback channels; F is the width of the signal baseband). It is assumed that both the FT and BSt have microcontrollers or other signal processing units synchronizing and controlling the work of the transmitter and receivers of FCS.

For every k-th cycle of transmission ($k = 1, \ldots, n$), microcontroller of the forward transmitter (FT) forms the residual signal $e_k = x - \hat{x}_{k-1}$ where $\hat{x}_{k-1}$ is the estimate of the sample computed by the processor of the BSt in previous cycle and delivered to the FT over feedback channel Ch2. Signal e_k is routed to the input of digitally controlled amplitude (AM) modulator-emitter. The signals emitted by FT $\tilde{y}_k$ have the form of high-frequency pulses of the same duration Δt_0:

$$y_k = A_0 M_k e_k = A_0 M_k (x - \hat{x}_{k-1}), (\hat{x}_0 = x_0), \tag{6}$$

where high-frequency (RF) components are omitted; A_0 is the amplitude of the carrier signal; and value of the modulation index M_k is set by the corresponding code previously written into the memory of the FT microcontroller, or delivered to the FT from the BSt over the feedback channel. After demodulation, the signal received by the BSt

$$\tilde{y}_k = A M_k e_k + \xi_k, \tag{7}$$

is routed to the processor of the BSt which computes a new estimate $\hat{x}_k$ of the sample according to the Kalman-type equation:

$$\hat{x}_k = \hat{x}_{k-1} + L_k \left[\tilde{y}_k - \mathrm{E}\left(\tilde{y}_k | \tilde{y}_1^{k-1}\right)\right], (\hat{x}_0 = x_0). \tag{8}$$

The variable A in (7) describes the amplitude $A = A_0\gamma/d$ of the received signal, which depends on the distance d between the FT and BSt, and on the channel gain γ dependent on the propagation losses, characteristics of environment, type and gains of antennas, etc. The gains L_k in (8) determine the rate of convergence of estimates $\hat{x}_k$ and their values, like the values M_k, are determined additionally free parameters stored in the memory of the BSt processor. Value $\mathrm{E}\left(\tilde{y}_k | \tilde{y}_1^{k-1}\right)$ in (8) describes the predicted mean value of the signal y_k computed in the processor of the BSt in previous cycle, and $\tilde{y}_1^{k-1} = \left(\tilde{y}_1, \ldots, \tilde{y}_{k-1}\right)$ denotes a sequence of signals received by the base station in previous cycles.

The BSt processor stores estimate $\hat{x}_k$ and sends it to the FT over the feedback channel. It also resets the gain L_k to the value L_{k+1} and prepares the physical receiver of the station to receive a new signal. Reception of the estimate by the FT initializes the next cycle of the sample transmission: microcontroller computes the residual (estimation error) $e_{k+1} = x - \hat{x}_k$, resets the gain M_k to the value M_{k+1}, and

FCS begins a new cycle of transmission. After n cycles, the final estimate $\hat{x}_n$ is routed to the addressee, while the system recovers its initial state and begins transmission of the next sample.

3.2 Principles and particularities of FCS and AFCS optimization

All the results of pioneering and later research in FCS optimization were obtained using *linear* models of FT transmitters, and this section presents the basic idea of these researches, as well techniques and results of FCS optimization for forward transmitters described by the linear model (7).

Models (6)–(8) are not abstract and describe the sequence of transformations of the signal along its transition over the real units and components of FCS, as well the influence of noises and distortions on the final result of transmission. Moreover, each of these models allows calculation of the changes in the statistical characteristics of signals after each subsequent transformation, and considers the most substantial particularities of this process influencing the work of the system.

Apart from the initially known (given) parameters, these models contain free parameters permitting the designers to regulate the work of particular units and improve the performance of the overall system. For the FCS under consideration, these parameters are $M_1, \dots, M_n$ and $L_1, \dots, L_n$. The basic criterion of the transmission quality is the accuracy ("fidelity" in [1]) of recovery of the signal that is MSE of its estimates $P_k = \mathrm{E}\left[(x - \hat{x}_k)^2\right]$.

The optimization of FCS begins from the definition of algorithm permitting to compute, using the received data $\tilde{y}_1^k$, optimal estimates $\hat{x}_k = \hat{x}_k\left(\tilde{y}_{1_1}^k\right)$ minimizing the MSE P_k for each $k = 1, \dots, n$. According to Bayesian estimation theory (see [33, 34]), in the Gaussian case, these are conditional averages $\hat{x}_k = E\left(x|\tilde{y}_1^k\right)$of random values observed in the presence of AWGN. Moreover, residuals $e_k = x - \hat{x}_k$ and values $\tilde{y}_k$ of the received signal have zero mean values and are mutually orthogonal [34]:

$$\mathrm{E}\left(e_k|\tilde{y}_1^{k-1}\right) = \mathrm{E}\left(x|\tilde{y}_1^{k-1}\right) - \hat{x}_{k-1} = 0; \tag{9}$$

$$\mathrm{E}\left(\tilde{y}_k|\tilde{y}_1^{k-1}\right) = AM_k\mathrm{E}\left(e_k|\tilde{y}_1^{k-1}\right) + \mathrm{E}\left(\xi_k|\tilde{y}_1^{k-1}\right) = 0; \tag{10}$$

$$\mathrm{E}(e_k e_m) = P_k\delta_{mk};\;\; \mathrm{E}\left(\tilde{y}_k\tilde{y}_m\right) = \left(\sigma_\xi^2 + A^2M_k^2\right)\delta_{mk}, \tag{11}$$

where δ_{mk} = 1 for $m = k$ and δ_{mk} = 0 for $m \neq k$.

Substitution of (10) into (8) results in algorithm computing optimal Bayesian estimates that takes an extremely simple form:

$$\hat{x}_k = \hat{x}_{k-1} + L_k\tilde{y}_k. \tag{12}$$

The full transmission-reception algorithm (6)–(8) permits to build a mathematical model of transmission process and to derive the following algorithm for calculation of the mean square error (MSE) of estimates formed by FCS in sequential cycles.

$$\begin{aligned} P_k = \mathrm{E}\left[(x - \hat{x}_k)^2\right] &= \mathrm{E}[(1 - AM_kL_k)\;(\hat{x}_{k-1} - x) + L_k\xi_k]^2 = \\ &= (1 - AM_kL_k)^2P_{k-1} + L_k^2\sigma_\xi^2, \end{aligned} \tag{13}$$

where $P_0 = \sigma_0^2$ and $\hat{x}_k = \mathrm{E}\left(x|\tilde{y}_1^k\right)$ are optimal Bayesian estimates (in this case Eq. (8) takes an extremely simple form(12)).

Free parameters M_k, L_k in the right-hand side of (13) do not depend explicitly on the previous values of gains $M_{1,\dots,}M_k$, $L_{1,\dots,}L_k$, which allows the following formulation of the optimization task:

For each k = 1,…,n, one should find values of *the gains* $M_{1,\dots,}M_k$, $L_{1,\dots,}L_k$, *which minimize, under additional conditions and constrains, the MSE of transmission* (13).

Beginning the first works, the most widely used additional condition was (and still remains) a constraint on the instant or average power of emitted signals W_0^{sign}. It cannot be greater than the power S_0 of the transmitter:

$$E\left[y_k^2\right] \le S_0 \quad \text{or} \ \frac{1}{n}\sum_{k=1}^{n} E\left[y_k^2\right] \le S_0. \tag{14}$$

Without loss of generality, one may assume that the power of the FT transmitter and the amplitude of emitted signals are connected by the relationship $S_0 = A_0^2$. In this case, substitution of formula (6) into (14) directly gives the expression for the set of permissible values of modulation index M_k:

$$M_k \le \frac{1}{A_0}\sqrt{\frac{S_0}{P_{k-1}}} = \frac{1}{\sqrt{P_{k-1}}}. \tag{15}$$

According to (13), for every M_k satisfying the inequality (15), MSE of transmission depends on the gains L_k, which in turn determine the rate of convergence of estimates $\hat{x}_k$ the input value x. The extremum of MSE in the set of L_k under definite $M_k$not violating condition (15) can be easily found, and the point of extremum is determined by the formula:

$$L_k^{opt} = \frac{AM_kP_{k-1}}{\sigma_\xi^2 + A^2M_k^2P_{k-1}} = \frac{1}{AM_k}\left(1 - \frac{P_k}{P_{k-1}}\right). \tag{16}$$

The substitution of (16) into (13) gives the following recurrence equation for the corresponding minimal values of MSE:

$$P_k = \frac{\sigma_\xi^2 P_{k-1}}{\sigma_\xi^2 + A^2M_k^2P_{k-1}} = \frac{P_{k-1}}{1 + Q_k^2P_{k-1}}, \tag{17}$$

where parameter $Q_k^2 = A^2M_k^2/\sigma_\xi^2$ describes the SNR at the output of the forward channel.

Formula (17) shows that greater values of modulation index M_k decrease the MSE P_k, that is, improve the quality of transmission. However, the increase of the values M_k is limited by condition (15), and the theoretically achievable minimum of MSE is achievable in practice only if these gains M_k are set to the values:

$$M_k^{opt} = \frac{1}{A_0}\sqrt{\frac{S_0}{P_{k-1}^{\min}}} = \frac{1}{\sqrt{P_{k-1}^{\min}}}; \ M_1^{opt} = \frac{1}{\sigma_0}, \tag{18}$$

where $P_{k-1}^{\min}$ is defined by Eq. (17) with the values M_k set to the values in (18). The result of the replacement determines the theoretically achievable lower boundary of MSE values described by the relationship:

$$P_k^{\min} = \sigma_0^2\left(1+Q^2\right)^{-k}; P_0 = \sigma_0^2, \tag{19}$$

where SNR $Q_k^2 = A^2 M_k^2/\sigma_\xi^2$ at the forward channel output is constant for each cycle of the sample transmission and takes the values:

$$SNR_k = Q_k^2 = \frac{W^{sign}}{\sigma_\xi^2} = \frac{1}{N_\xi F_0}\left(\frac{A_0\gamma}{d}\right)^2 = Q^2. \tag{20}$$

Claim 1: Relationships (6)–(8) with the parameters M_k, L_k set, for each $k = 1, \dots, n$, to the values (16) and (18) determine the optimal transmission-reception algorithm, which contains the information permitting us to design optimal FCS transmitting signals with maximal accuracy (minimal MSE), and this boundary is determined by formula (19). Greater accuracy is not feasible.

Moreover, the optimal transmission-reception algorithm permits us to compute the information characteristics of optimal AFCS prior and posterior entropies, as well as the mean amount of information in estimates $\hat{x}_k$ regarding the values of input samples x:

$$H(X) = \frac{1}{2}\log_2\left(2\pi e\sigma_0^2\right); H\left(X|\hat{X}_k\right) = \frac{1}{2}\log_2(2\pi e P_k); \tag{21}$$

$$I\left(X,\hat{X}_k\right) = H(X) - H\left(X|\hat{X}_k\right) = \frac{1}{2}\log_2\left(\frac{\sigma_0^2}{P_k}\right). \tag{22}$$

Taking into the account that the amount of information (22) in estimates is achieved in k cycles, that is, during the time $T_k = k\Delta t_0$, formulas (22) and (19) permit us to evaluate the current values of bit rate of the signal transmission:

$$\begin{aligned} R_{\max}^{FCS} &= \frac{I_{\max}\left(X,\hat{X}_k\right)}{k\Delta t_0} = F_0\log_2\left(\frac{\sigma_0^2}{P_k^{\min}}\right) = \\ &= F_0\log_2\left(1+Q^2\right) = F_0\log_2\left(1+\frac{W^{sign}}{N_\xi F_0}\right) = C[\text{bit/s}]. \end{aligned} \tag{23}$$

Claim 2. Formula (23) is identical to Shannon's formula (1) and determines the limit bit rate of transmission, that is, the capacity of the system. Moreover, attaining the boundary (23) means that spectral and energy efficiencies of the FCS also attain their limit values and are connected through Shannon's relationship (3). Let us stress that, unlike CSC, the presented relationships determine the approach to the optimal FCS design.

Similar results were obtained in [4, 6, 9] and other works. However, regardless of their correctness, neither the above nor earlier obtained algorithms of transmission in any of their versions could be implemented in practice. Analysis of the reasons showed that the main reason was the omission of saturation effects in the FT.

Another, not less critical reason, and not counted in all formulations of the optimization tasks, has been noted in Section 2, that is, the local dependence of the quality of transmission on the scenario of FCS application. The presented above results confirm this fact directly: values of optimal parameters M_k, L_k as well as all other characteristics of optimal FCS depend on the distance between the FT and the BSt, so that and changes in the FCS's position or surrounding violate the perfect mode of transmission.

In the following sections, we show that modulation and feedback may resolve or at least substantially reduce these problems and make the perfect FCS feasible.

3.2.1 Influence of FT saturation and its elimination

Signals $e_k = x - \hat{x}_{k-1}$ at the input of AM modulators repeat the error of the sample estimate formed in BSt in previous cycle, and their variance is equal to the MSE P_k. This allows the modulation gains to be set, in each cycle, to greater and greater values, which increases SNR at the output of the forward channel and provides superfast growth of the accuracy of the estimates unachievable without feedback.

However, externally completely correct additional condition (14) does not count possible saturation of the modulators or emitters, if the signals $e_k = x - \hat{x}_{k-1}$ exceed their linear range, and an adequate model of the transmitter is to have the form (see also **Figure 2**):

$$y_k = A_0 \begin{cases} M_k e_k & \text{if } \hat{M}_k |e_k| \le 1 \\ \text{sign}\,(e_k) & \text{if } \hat{M}_k |e_k| > 1 \end{cases}. \tag{24}$$

In real FT, output range $[-A_0, A_0]$ is fixed except in particular cases, and the width of its input range depends on the value of modulation gain M_k. Setting the values M_k and omitting a consideration of statistics of the signals $e_k = x - \hat{x}_{k-1}$ excludes a possibility of considering saturation of the FT, which appears, if the signal $y_k = A_0 M_k e_k$ crosses the boundaries of its output range. It is worth adding that each saturation during the sample transmission distracts its estimate and causes irreversible loss of information about the sample value.

The probability of the first saturation of FT would appear in the k-th cycle and can be easily evaluated: both signals e_k and y_k are zero mean Gaussian values, and their variances are known. The not complex calculations yield the following relationship:

$$\begin{aligned} \Pr_k^{sat} &= \Pr\left(|y_k| \ge A_0 |\, \tilde{y}_1^{k-1}\right) = \Pr\left(|e_k| \ge 1/M_k |\, \tilde{y}_1^{k-1}\right) \\ &= 1 - \frac{1}{\sqrt{2\pi P_{k-1}}} \int_{-1/M_k}^{1/M_k} \exp\left(-\frac{e_k^2}{2P_{k-1}}\right) de_k = 1 - 2\Phi\left(\frac{1}{M_k P_{k-1}}\right), \end{aligned} \tag{25}$$

where $\Phi(x)$ is a tabulated Gaussian integral (5).

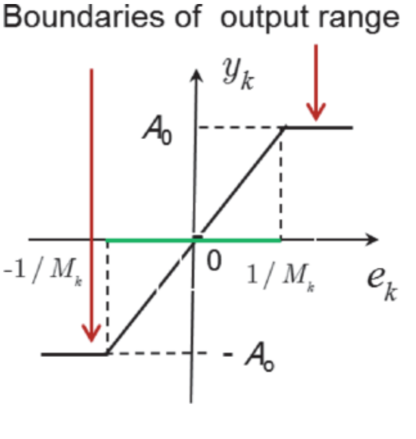

Figure 2.
Static transition characteristic of the transmitter with a finite output range.

Substitution of formula (18) into (25) gives the following evaluation of the probability of the first saturation in k-th cycle of transmission, beginning with the first cycle:

$$\Pr_k^{sat} = 1 - 2\Phi(1) \approx 1 - 0.68 = 0.32,$$

and the probability of its appearance during first five cycles of transmission attains the value $\Pr_{1 \div 5}^{sat} = 1 - (1 - P^{sat})^5 = 1 - 0.68^5 \approx 0.85$ and quickly tends to unity in next cycles.

One should add that MSE of estimates is weakly sensitive to sufficiently rare cases of FT saturation. However, taking into account that each instance of saturation causes a loss of the sample and $I(X, \hat{X}_n)$ bits of information, the probability of saturation determines the mean percent of erroneous bits in binary sequences delivered to the addressee. These losses can be considered as the BER of transmission (rather bit word error rate—WER but numerically these values are equal). Value of the BER is one of the key characteristics of CSC, and the general tendency in modern communications is to decrease its values to $10^{-6} \div 10^{-8}$ and lesser. Therefore, the setting of modulation index requires closest attention. Investigations showed that the severity of this problem can be sufficiently reduced by employing the feedback channel.

Claim 3. The linear models of the transmitters that are commonly used in formulations of optimization tasks and constraint on the mean power of emitted signals describe the work of transmitters inadequately. This has been and still remains one of the main reasons why FCSs have not been implemented in practice. The solution of this problem allowed for the application of the "statistical fitting condition" [35].

3.2.2 Statistical fitting condition

The previous section and formula (25) show that saturation of the FT can be almost eliminated if the gains M_k are set to the values that guarantee the probability of saturation not greater than a given small $\mu << 1$, (e.g., $\mu \sim 10^{-4} \div 10^{-8}$) for every sequence $\tilde{y}_1^{k-1}$:

$$\Pr_k^{sat} = \Pr\left(|y_k| \geq A_0 |\, \tilde{y}_1^{k-1}\right) = 1 - \int_{-1/M_k}^{1/M_k} p\left(e_k|\tilde{y}_1^{k-1}\right) \mathrm{d}e_k == 1 - 2\Phi\left(\frac{1}{M_k P_{k-1}}\right) \leq \mu. \tag{26}$$

Under fulfilled condition (25), the probability of the sample saturation has the value $1 - (1 - \mu)^n \approx n\mu << 1$. This means almost always (at the confidence level $1 - n\mu$), the FCS would work in optimal mode without saturations, and the percent of erroneous bits would not be greater than μ.

Relationship (26) determines the set of permissible values of the gains M_k and its upper boundary. These values make (26) the equation which, after replacement of the values $1/M_k P_{k-1}$ by the variable α, gives the following relationships for the permissible maximal (optimal) values of modulation gains:

$$M_k^{opt} = \frac{1}{\alpha \sqrt{P_{k-1}^{\min}}}; (k = 1, .., n), \tag{27}$$

where parameter a satisfies the equation:

$$\Phi(\alpha) = \frac{1}{\sqrt{2\pi}} \int_0^\alpha \exp\left(-\frac{z^2}{2}\right) \mathrm{dz} = \frac{1-\mu}{2}. \tag{28}$$

Claim 4. Setting the modulation index to the values (27) prevents the appearance of saturation and the FCS with non-linear FT transmits the signals almost always in linear mode.

Claim 5. Setting the gains M_k to the values (27) not only removes saturation but also:

a. reduces α times the amplitude of emitted signals: $A_0 \to A_0/\alpha$,

b. reduces α^2 times the power of emitted signals and SNR at the output of the channel:

$$W^{sign} = \frac{A^2}{\alpha^2}; SNR_k = Q_k^2 = \frac{W^{sign}}{\sigma_\xi^2} = \frac{1}{N_\xi F_0}\left(\frac{\gamma A_0}{\alpha d}\right)^2 = Q^2. \tag{29}$$

The structure and form of the basic relationships for the MSE, bit rate, and effectiveness remain the same. Changes in Shannon's formula (23) for the capacity and in the other relationships affect only the values of amplitude and power of emitted signals (29).

Claim 6. Reduction of the power of the emitted signal decreases the SNR and capacity of the system but makes the perfect FCS feasible, and these systems transmit signals with limit energy-spectral efficiency optimally, as well as completely utilizing the frequency and energy resources of the FT. Moreover, the absence of coders reduces their energy consumption.

To distinguish the considered systems and the FCS, and to focus on the new systems, in what follows, we use a new abbreviation to refer to these systems: AFCS (adaptive FCS).

Let us remind that these relationships were derived under assumption that the feedback channels are ideal. This is not an unrealistic suggestion: relatively inexpensive modern CSCs provide virtually error-free short-range transmission. If necessary, the quality of the channel can also be improved by increasing the power of transmitters—the BSt have sufficiently large, if not unlimited energy resource.

We should add that the discussed relationships are a particular case of the more general optimal transmission-reception algorithm for the statistically fitted AFCS with noisy feedback [36–39], see also **Table 1** below. It is worth stressing that these algorithms have the same structure and form as those presented in pervious sections. The only but principle difference concerns the expression for the MSE of transmission, which takes the form:

$$P_k^{\min} = \frac{\left(\sigma_\xi^2 + A^2 M_k^2 \sigma_\nu^2\right) P_{k-1}^{\min}}{\sigma_\xi^2 + A^2 M_k^2 \left(\sigma_\nu^2 + P_{k-1}^{\min}\right)} = \left(1+Q^2\right)^{-1}\left[1 + Q^2 \frac{\sigma_\nu^2}{\left(\sigma_\nu^2 + P_{k-1}^{\min}\right)}\right] P_{k-1}^{\min}, \tag{30}$$

where variable σ_ν^2 is the variance of the errors v_k in the signals (controls) $\hat{x}_k$ transmitted from the BSt to FT over the feedback channel with AWGN. Under $\sigma_\nu^2 = 0$, this formula coincides with (17). Analysis of formula (30) gives comprehensive answers to many questions concerning the behavior of feedback systems.

	Algorithm	Parameters
Initial values	$\hat{x}_0 = x_0$	$P_0 = \sigma_0^2$
Signal at the modulator input	$e_k = x - \hat{x}_{k-1} + v_k$	$\alpha : \frac{1}{\sqrt{2\pi}} \int_0^{\alpha} \exp\left(-\frac{z^2}{2}\right) dz = \frac{1-\mu}{2}$
Emitted signal	$y_k = A_0 M_k e_k$	$M_0 = \frac{1}{\alpha\sigma_0}; M_{k/k\geq 1} = \frac{1}{\alpha\sqrt{\sigma_\nu^2 + P_{k-1}}}$
Received signal	$\tilde{y}_k = A y_k + \xi_k$	$A = \frac{\gamma}{d} A_0$
Estimate computing	$\hat{x}_k = \hat{x}_{k-1} + L_k \tilde{y}_k$	$L_k = \frac{A M_k P_{k-1}}{\sigma_\xi^2 + A^2 M_k^2 P_{k-1}} = \frac{1}{A M_k}\left(1 - \frac{P_k}{P_{k-1}}\right)$
Basic equation for MSE	$P_k = \left(1 + Q^2\right)^{-1}\left[1 + Q^2 \frac{\sigma_\nu^2}{\left(\sigma_\nu^2 + P_{k-1}\right)}\right] P_{k-1}; k = 1, \ldots, n$	

Table 1.
Basic relationships for modeling and design of optimal AFCS with non-ideal feedback channel ($\sigma_\nu^2>0$; index "opt" in the parameters M_k^{opt}, L_k^{opt} is omitted).

The main result is the confirmation that the capacity of FCS and AFCS does not depend on the feedback noise in the initial interval of the sample transmission, and is determined by Shannon's formula (1). However, since the moment n^*, when the MSE of estimates attains the values of σ_ν^2 order, the capacity of AFCS begins to decrease and monotonically tends to zero ([36] and later works).

A summary of the relationships sufficient for the development of a MATLAB model of optimal AFCS and simulation experiments is presented in **Table 1**. Moreover, these seemingly simple relationships were used to design a prototype (demonstrator) of the perfect AFCS, discussed in the next section.

If a relative error of the sample transmission $\delta = \Delta/\sigma_0$ is to be attained in minimal time, and feedback is ideal, absolute error Δ of the final estimates should be not greater than σ_ν, and the corresponding minimal time of transmission is of the order:

$$T_\delta = \frac{n_\Delta}{2F_0} = -\frac{1}{2F_0 \log_2\left(1 + Q^2\right)} \log_2\left(\frac{\Delta^2}{\sigma_0^2}\right) = -\frac{\log_2 \delta}{C^{Ch1}}. \tag{31}$$

where n_Δ determines the necessary number of cycles (see e.g. formula (27) in [37] or (22) in [38]). Formula (31) also determines the baseband $F \leq F_\delta = C^{ch1}/2 \log_2 \delta$ of the signals that can be transmitted by the AFCS at maximum rate, with the given accuracy and limit energy-spectral efficiency.

3.2.3 Particular role of MSE criterion

As noted above, the basic criterion for transmission quality is the accuracy (in [1] "fidelity") of the signals' recovery. For the CS transmitting analog signals, this is the MSE of their estimates. The importance of MSE is due to several factors. First of all, for arbitrary linear channels with AWGN, which transmit Gaussian signals, MSE P_k determines the amount of information determined by following general relationship ([32, 34], see also (22)):

$$I\left(X, \hat{X}_n\right) = \frac{1}{2} \log_2\left(\frac{\sigma_0^2}{P_n}\right) \text{ [bit/sample]}. \tag{32}$$

So, if CSs transmit the samples each in n cycles, that is, during $T_n = n\Delta t_0 = n/2F_0$ [s], the final estimates $\hat{x}_k$ deliver to addressee the amount of information with the bit rate

$$R_n = \frac{I(X, \hat{X}_n)}{n\Delta t_0} = F_0 \log_2\left(\frac{\sigma_0^2}{P_n}\right) \text{ [bit/s]}, \tag{33}$$

independent of whether the system is optimal or not. This value determines the spectral efficiency of the sample transmission R_n/F_0 that is at the AFCS output.

The iterative principle of transmission permits us to introduce the measure more informative than (33): the *instant* bit rate, determined by the following relationship:

$$\Delta R_k = \frac{I(X, \hat{X}_k) - I(X, \hat{X}_{k-1})}{\Delta t_0} = F_0 \log_2 \frac{P_{k-1}}{P_k} \text{ [bit/s]}, \tag{34}$$

which describes the increment of information in sequentially computed estimates $\hat{x}_k$, $(k = 1, \dots, n)$. In turn, formulas (33) and (34) define the final and instant spectral efficiencies of transmission, respectively:

$$\frac{R_n}{F_0} = \frac{1}{n} \log_2 \frac{\sigma_0^2}{P_n}; \frac{\Delta R_k}{F_0} = \log_2 \frac{P_{k-1}}{P_k}. \tag{35}$$

The general expression for the energy efficiency of transmission can be defined as follows:

$$\frac{E_n^{bit \text{ AFCS}}}{N_\xi} = \frac{W_n^{sign}}{N_\xi R_n} = \frac{n W_n^{sign}}{N_\xi F_0 I(X, \hat{X}_n)} = \frac{nQ^2}{\log_2 \frac{\sigma_0^2}{P_n}}, \tag{36}$$

which shows that, unlike spectral efficiency, this characteristic of the CS performance depends not only on the MSE, but also on the SNR Q^2 at the forward channel output, which requires additional measurement.

Another particularity of the MSE, which is not currently utilized in communications, is its analytical formulations have empirical analogs, as well as well-studied and widely used methods of their evaluation. In our research, the following method is used. However, as it follows from (36), evaluation of the energy efficiency, in the general case, requires additional measurement of SNR Q^2. In our research, the following method is used.

The FT generates and sends to the BSt a testing sequence of M random Gaussian samples $\left(x^{(1)}, \dots, x^{(M)}\right)$ each generated with the same mean value x_0 and variance σ_0^2 using corresponding codes written into memory units of microcontrollers of the FT transmitter and processor of the BSt (or generated by PC). The BSt processes the received signals, computes optimal estimates $\left(\hat{x}_1^{(1)}, \hat{x}_2^{(1)} \dots, \hat{x}_{n-1}^{(M)}, \hat{x}_n^{(M)}\right)$ of input samples which, and stored values $\left(x^{(1)}, \dots, x^{(M)}\right)$, allow to compute empirical values of the MSE P_k using the known relationship:

$$\hat{P}_k = \frac{1}{M} \sum_{m=1}^{M} \left[x^{(m)} - \hat{x}_k^{(m)}\right]^2, (k = 1, \dots, n) \tag{37}$$

next used for the evaluation of the bit rate (35) and energy-spectral efficiency of AFCS. In practice, it is more convenient to compute these values using the MSE expressed in dB:

$$\text{MSE}_k[\text{dB}] = 10 \log_{10}\left(\frac{\hat{P}_k}{\sigma_0^2}\right) \text{ [dB]}. \tag{38}$$

as well as normalized root square (relative error of transmission) $\delta = \sqrt{P_k}/\sigma_0$.

3.3 Adaptive auto-adjusting AFCS to the scenario of application

The adjusting algorithm uses the "resonance" effect that is increase of MSE, if the values of parameters L_k, M_k decline from their optimal values (16), (27). The effect is illustrated in **Figure 3** which shows the changes of relative errors of transmission $\delta = \sqrt{P_k}/\sigma_0$ (normalized root mean square error—RMS) under gains M_k set to the values (27) and gain $L_k^* = L_k(1 + \delta_L)$, where L_k has the value (16) and δ_L is a variable parameter.

To adjust the parameters, the system utilizes two identical testing sequences of Gaussian samples $\left(x^{(1)}, \dots, x^{(M)}\right)$ whose codes are stored in the memory of the BSt processor and the FT microcontroller (or BSt transmits these sequences to FT over feedback). All the samples in the testing sequence are zero mean Gaussian values with known variance σ_0^2.

In the first cycle, the modulation index M_1^{opt} is set to the known value $1/\alpha\sigma_0$, and the FT sends to the BSt the written testing sequence of samples $\left(x^{(1)}, \dots, x^{(M)}\right)$, the same one that is stored in the processor of BSt. The BSt processor computes the estimates $\left(\hat{x}_1^{(1)}, \dots, \hat{x}_1^{(M)}\right)$ and values of MSE P_1. It also searches for the minimizing MSE value $\hat{L}_1^{opt}$ and computes the corresponding value $\hat{P}_1^{\min}$. The computed values $\hat{L}_1^{opt}$, $\hat{P}_1^{\min}$, and $\left(x^{(1)}, \dots, x^{(M)}\right)$ are stored. Simultaneously, the BSt sends values $P_1^{\min}$ and estimates $\left(\hat{x}_1^{(1)}, \dots, \hat{x}_1^{(M)}\right)$ to the FT. Reception of these data initiates the second cycle of AFCS adjusting:

In this cycle, the microcontroller of the FT forms the sequence of signals $e_2^{(m)} = x - \hat{x}_1^{(m)}$, $(m = 1, \dots, \mathrm{M})$, computes the optimal value of the gain $M_2^{opt} = 1/\alpha\sqrt{P_1^{\min}}$, and sets the gain of AM modulator to this value. So adjusted, the FT transmits the sequence of signals $y_2^{(m)} = A_0 M_2^{opt} e_2^{(m)}$ to the BSt, which processes the received sequence in the same way as in first cycle. The computed values $P_2^{\min}, L_2^{opt}$ are stored, sequence $\left(\hat{x}_1^{(1)}, \dots, \hat{x}_1^{(M)}\right)$ is replaced by the new sequence $\left(\hat{x}_2^{(1)}, \dots, \hat{x}_2^{(M)}\right)$, and together with $P_2^{\min}$ is transmitted to the FT. The receipt of these values initializes the next cycle of adjusting realized according to the same scheme as in the previous cycle. The subsequent cycles repeat these operations. After the M-th cycle, the adjusted AFCS begins nominal functioning.

The duration and frequency of adjustments depend on the dynamics of scenario changes, processors' rate, channel bandwidth, requirements for the accuracy of estimates, environmental characteristics, and other factors.

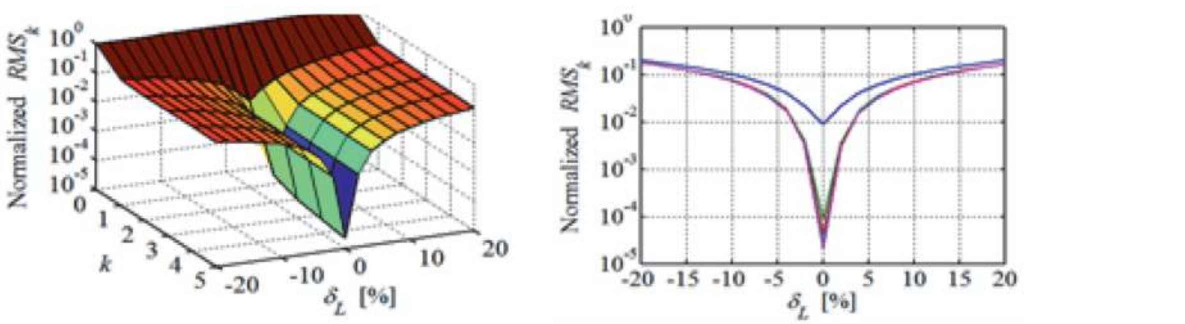

Figure 3.
Changes of mean relative error of estimates depending on the deviation of the gains L_k *from optimal values* L_k^{opt} *under fixed optimal gains* M_1^{opt}.

4. Experimental study of AFCS functioning

The prototype of AFCS was designed on the basis of the optimal transmission-reception algorithm(6)–(8), using and parameters set to the values (16), (18), (or in **Table 1**, for $\sigma_v^2 = 0$), and general principles of AFCS transmission described in Section 3.1. The layouts of the transmitting (FT) and receiving (BSt) modules are shown in **Figure 4a**, **b**.

The transmitter was realized using narrowband adaptive AM modulator followed by the programmable voltage-controlled oscillator VG7050EAN (power 10 dBm, carrier frequency 433.2 MHz). The feedback channel was realized using digital receiver RFM31B-S2 and transmitter RFM23B (power 27 dBm, carrier frequency 868.3 MHz). This ensured virtually ideal feedback transmission of signals in the indoor and outdoor experiments carried out at distances to 100 meters (straight line view, FT with ceramic mini-antennas, BSt with quarter-wave antennas).

At the beginning of every new series of experiments, a self-adjusting algorithm was activated, which set the parameters M_k and L_k to the values optimal for the given scenario.

The main measured characteristic of the prototype was the *dependence of* MSE_n[dB] *on the number of transmission cycles. The experiments were* carried out at different distances between the FT and BSt. Typical dependencies of MSE_n[dB] on n at the distances of 40, 50, and 75 meters are shown in **Figure 5**.

The plots are presented in the decibel scale, and the nearly linear dependence of the measured values MSE_n[dB] on the number of cycles means that, on a linear scale, MSE decreases exponentially. According to the results of Section 3.2 (formula (19)), this is possible, if the system transmits signals perfectly, with a bit rate *equal to the capacity* of the system. In this case, spectral and energy efficiencies of transmission also attain the limit values.

Moreover, plots in **Figure 5** allow for a sufficiently accurate evaluation of the characteristics of the system. With this aim, let us rewrite the expression of spectral efficiency (33) in the decibel scale in the form (the confirmed close to perfect transmission permits us to write that $R = C$):

$$\frac{C_n}{F_0} = \frac{3.32}{n} \log_{10} \frac{\sigma_0^2}{P_n} = -\frac{0.332}{n} \text{MSE}_n[\text{dB}]. \tag{39}$$

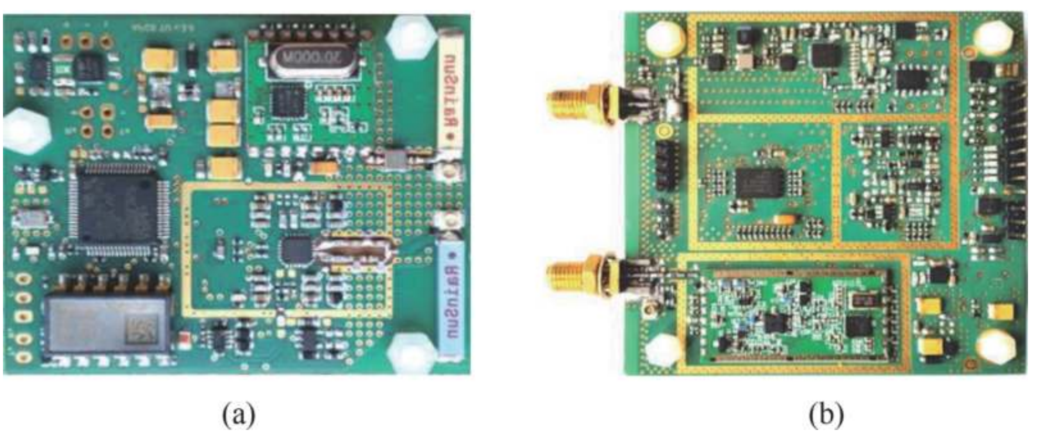

Figure 4.
Layout of PCB modules of prototype of perfect AFCS: (a) forward transmitter integrated with sensor; (b) base station.

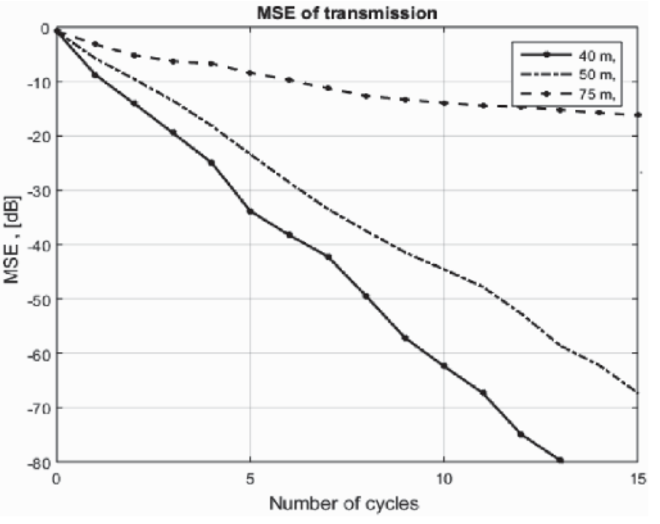

Figure 5.
Values $\mathrm{MSE_k[dB]} = \mathrm{f(k)}$ *measured at the distances of 40, 50, and 75 meters (indoor experiments).*

Distance (m)	40	50	75
MSEn [dB]/n	−6.25	−4.4	−1.4
C^{syst}/F_0	2.07	1.46	0.465
Q^2	3.21	1.75	0.375
$E_n^{bit\ syst}/N_\xi$	1.76	1.19	0.8
$E_n^{bit\ syst}/N_\xi$ [dB]	1.85	0.76	−0.92

Table 2.
Measured characteristics of the prototype.

The linear approximation of the plots in **Figure 5** in first $n = 10$ cycles allows for evaluation of the ratio $\mathrm{MSE}_n[\mathrm{dB}]/n$ directly from the plots. Substitution of these values into (39) gives the numerical estimates of the spectral efficiency for each distance. In turn, perfect mode of transmission allows for the evaluation of the power efficiency using formula (3) and measured values of the spectral efficiency C_n/F_0. The obtained results are presented in **Table 2** and illustrated on the energy-spectral plane in **Figure 6**.

The plots in **Figure 7a**, **b** illustrate the results of measurements carried out at the fixed distance sequentially, with the time interval in 1–3 minutes.

All the experiments confirmed the existence of the initial interval $1 \le k \le n^*$ of the perfect transmission, as well as the efficiency of the developed algorithm of AFCS auto-adjusting. On average, at the distances of 40–50 m, the accuracy of transmission attained the values of 10^{-4} order in 5÷7 cycles of the sample transmission. In several experiments, accuracy attained the order of $10^{-7} \div 10^{-10}$ and greater, but the results were non-stable (see, e.g., plots in **Figure 7a**, **b**).

It was also noted the growing influence of the external disturbances and noises on the further changes of MSE if it attained sufficiently small values. Since this time, MSE decreased with the growing fluctuations, sometimes regularly but at the smaller rate. This could not be an effect caused by saturations: experiments were carried out under saturation factor $\alpha = 3$ that reduced the cases of saturations to 0.5–1 percent of the transmitted samples. A study of the AFCS functioning in real

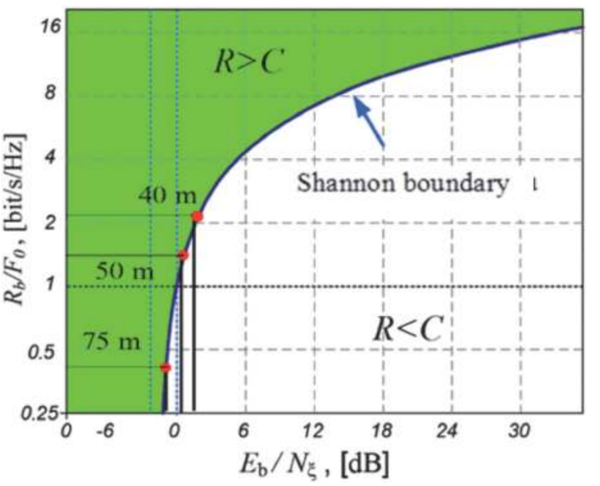

Figure 6.
Two-dimensional plot presenting values (red points) of the energy-spectral efficiency of optimal AFCS measured at the distances in 40, 50, 75 meters.

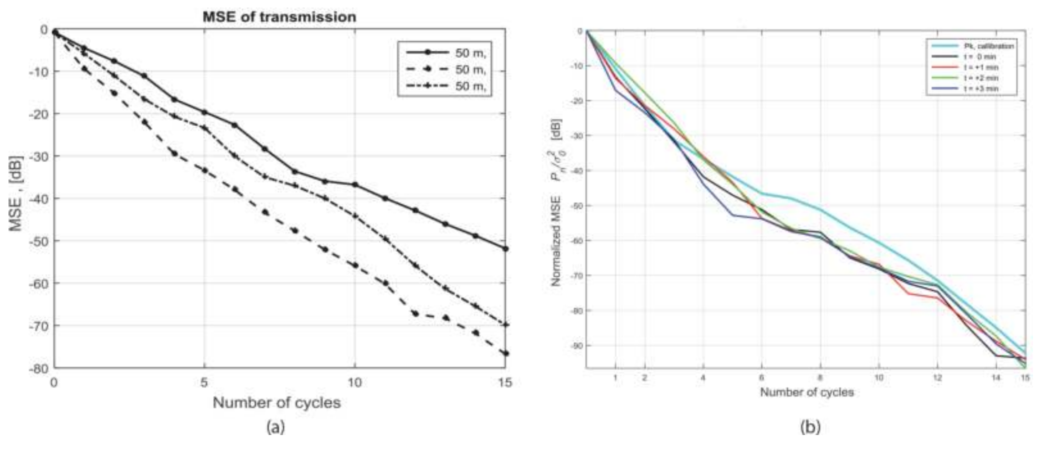

Figure 7.
Dependencies $MSE_k[dB] = f(k)$ *measured with the intervals in 2–3 minutes at the distance of 50 m (indoor experiments): (a) power of FT transmitter 10 mW, ceramic mini-antennas; (b) power of FT transmitter 1 mW, quarter-wave antennas.*

conditions is to be continued. It is worth noting that the utilization of the quarter-wave antennas provided sufficiently stable sample transmission at distances upto 80–90 m using FT with the power reduced to 1 mW.

The experiments confirmed the feasibility of the perfect AFCS, as well as the capability of modulation and feedback to ensure the perfect signal transmission.

5. Discussion of results

The chapter gives a brief outlook of the approaches to design of the currently not used class of communication systems which may substantially improve the efficiency and performance of the wireless low-power transmission. The presented results develop excellent but not finished and today almost forgotten research in FCS theory carried out in the years 1960–1970. These investigations were first steps toward the formation of the second direction in information theory: the theory of the systems with feedback channels. However, in the middle of 70s, the research was hampered.

The main reason for the difficulties was the lack of practical results. Another, less obvious source of failures was the omission of possible saturation of modulators or emitters in the forward transmitters. The not less crucial obstacle also was not discussed in the literature which is the dependence of the CS performance on the scenarios of application.

The chapter shows how modulation and feedback permit to resolve these difficulties. The results of research confirm the general conclusion of the pioneering research: FCS may transmit signals without coding perfectly, that is in real time, with a bit rate equal to the capacity of systems, and with the limit accuracy of the signals recovery. Moreover, the only difference between the relationships presented in the chapter and those presented in earlier works is the numerical values of modulation index.

The rapidly developing wireless networks (WN) utilize a great number of short-range low-energy end-node (EN) transmitters. Nowadays, all of them employ the coding and advanced digital technical solutions. The level and number of requirements for EN transmitters grow permanently. However, as noted by many authors, possibilities to improve the performance of the PHY layer of WN are almost exhausted. We discussed this in the beginning of the chapter. Moreover, all networks utilize, on the mass scale, feedback channels.

What can we conclude? Despite its great merits, coding is losing its advantages and is being used in low-power EN transmitters designed for the short-range transmission ("one mile zone" and shorter). The main task of these transmitters is the reliable and secure delivery of relatively small amounts of information to the BSt or master node, if possible, with minimal delay. The great rates (except for rare exclusions) are not necessary: this is the task for BSt which communicate with other BSt or higher level stations.

Today's problems of the EN transmitters design are prosaic: they should be as less energy-consuming as possible to increase the duration of continuous work ("lifetime") and to reduce the requirements of the energy sources. They should be resistant to inter-channel disturbances caused by nearby EN, as well as should have minimal complexity to decrease the production and deployment costs. It is also desirable that they have low emission, small size, light units, etc.

Reduction of the energy consumption inevitably causes the reduction of the power of the EN transmitters and that crucially decreases the quality and range of transmission. Compensation of the losses requires application of more efficient correcting codes and more complex coders, as well as the extension of the channel bandwidth. In turn, wide band transmission creates sufficiently powerful inter-channel disturbances in closely placed EN. The result is the appearance of complex technical solutions suppressing these distortions or, vice versa, utilizing them for improvement of the signals recovery. The list of tradeoffs between different requirements of the systems is large, and coding has no efficient answers to these questions.

Having no alternatives, the industry has no other choice but to transfer known principles of long-distance CS with coding (CSC) design and technologies to the design of low-power EN transmitters produced on the scale by the orders greater than powerful CSC transmitters. The not too essential for long-distance communications, constraints on the power of the transmitters, requirements for the bandwidth and other constrains became the crucial considerations in the wireless EN design. From our point of view, the greatest stumbling block is that CSCs do not allow for a development of the systematic approach to their optimization similar to the Bayesian approach described in the chapter. Codes have no parameters permitting their adjustment to the changes of characteristics of the channel, nor allow the formulation of mathematical models accounting for all the transformations of signals as they pass through the transmitter, channel, and receiver. AFCSs do have such possibilities.

Moreover, the signals generated by the transmitters of CSC are discrete, their form is fixed and in no way depends on the input signals. Information is delivered by combinations of the symbols of code. There is no possibility to regulate the quality of the transmission aside from the external regulation of the power of transmitter or switching the codes. Meanwhile, the quality of transmission provided by the adjusted perfect AFCS depends on the scenario of their application, but always attains the limit or close to the limit values.

General evaluation of the future perspectives of AFCS: currently, almost all CS and networks have feedback channels, and AFCS could solve many of the aforementioned and other problems. Below, we attach a summary of possibilities of the perfect AFCS, which have been established and verified in [36–41] and other works.

1. Perfect AFCSs provide the most energy-spectral efficient transmission of signals in real time with the limit energy-spectral efficiency, bit rate equal to the capacity of forward channel, and minimal MSE of the signals reception.

2. The absence of coders allows for the construction of a full mathematical model of transmission, from the source of signals to the BSt processor. This model enables the formulation of a clear analytical criterion (MSE), the application of Bayesian estimation theory, and the derivation of optimal transmission-reception algorithms determining the approach to the perfect AFCS design.

3. Feedback channel and optimal transmission algorithms enable the development of adaptive algorithms adjusting the parameters of AFCS to the environment changes. This permits the system to maintain the perfect mode of transmission in different, also non-stationary scenarios. De facto, the system regulates its own capacity, adjusting it to the changes of environment.

4. The side effect of AFCS adjustment is that the BSt computes the on-line estimates of MSE, SNR, and capacity of the system. These data permit to evaluate the current energy-spectral efficiency of transmission and to decrease the losses of energy regulating the number of cycles maintaining the required accuracy of the signal recovered.

5. The analytical expression for MSE of transmission has an empirical analog, whose values can be measured and used for evaluation of the performance of every CS used for the analog signals transmission. As shown in Section 3, MSE permits us to determine the quality of transmission, bit rate, as well spectral efficiency of every CS. For the perfect AFCS, minimal MSE determines the energy efficiency of transmission.

6. Signals emitted by the FT have the form of realizations of the (stationary) pulse white Gaussian noise. The amplitudes of each emitted pulse depend on random values of the signals e_k at the input of the modulator, and values of the adjusted parameters M_k depend on the scenario, which excludes data interception and ensures secure forward transmission. The full protection of the system depends on protecting the feedback channel and can be provided by applying well-protected codes and directed antennas.

7. The absence of coding units simplifies the architecture of the FT, as well as reduces their energy consumption, complexity, and cost, which allow for the development of efficient battery-less AFCS.

8. The FT transmitters can be realized in analog, digital, and mixed technologies. The results of analysis show that the most preferable form of realization would be the software implementation of the FT. Optimal transmission-reception and adjusting algorithms contain all basic information for the development and implementation of the software (SDR) version of the FT. Moreover, this software can be used for the reconfiguration of transmitters and the extension of possibilities of their utilization and functional possibilities of the EN as a whole.

9. Preliminary research [42] showed that perfect AFCS can be also used, virtually without modification of transmission scheme and algorithms, for the transmission of short codes. These codes can be parts of the longer code routed to the input of the AFCS or formed by digital sensors. The set of the codes can be converted into the uniform set of analog values, and high accuracy of AFCS transmission will ensure reliable resolution of the received signals.

10. The designed prototype of AFCS is the first "living" example of the system that transmits signals without coding perfectly, and this was confirmed by the results of experiments.

Most of the listed capabilities of AFCS are not feasible for the CS with coding.

In this chapter, we considered only scalar (point-to-point) AFCS which employ the AM transmission, but the theory allows for the extension to optimization of the multi-channel FCS. Moreover, AM is only one of three types of modulation, and each has its own limited operating range. It would be important to investigate the systems with the FM and PM modulations—this could give a new classes of perfect FCS transmitting signals without abnormal errors and with the limit energy-spectral efficiency. It is also worth noting that statistical fitting condition (26) can be used for the optimization of different classes of estimation, controlling, measurement, and signal processing systems.

In conclusion, let us repeat the questions asked in [19]: "Is the PHY layer dead? ... whether the research directions taken in the past have always been the right choice and how lessons learned could influence future policy decisions?"

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Acronyms

CS	communication system
CSC	communication system with coding
FCS	feedback communication system
AFCS	adaptive feedback communication system
WN	wireless network
EN	end node
FT	forward transmitter

BSt	base station
PHY	physical layer of network
AWGN	additive white Gaussian noise
SNR	signal-to-noise ratio
BER	bit error rate
MSE	mean square error
MMSE	minimal mean square error
RMS	root mean square

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