Design of Self-Organized Intelligent Control Systems based on Quantum Fuzzy Inference: Intelligent System of Systems Engineering Approach

Sergey V. Ulyanov[1] **and Ludmila V. Litvintseva**[1]
[1] YAMAHA Motor Europe N.V. R&D Office, Via Bramante, 65, 26013-Crema (CR) Italy
Phone:+390373204438 Fax: +390373204518, email: ulyanov@yamaha-crema.it

Abstract: *This report presents a generalized design strategy of intelligent robust control systems based on quantum/soft computing technologies that enhance robustness of fuzzy controllers by supplying a self-organizing capability. It is demonstrated that fuzzy controllers prepared to maintain control object in the prescribed conditions are often fail to control when such a conditions are dramatically changed. We propose the solution of such kind of problems by introducing a generalization of strategies in fuzzy inference from a set of pre-defined fuzzy controllers by new Quantum Fuzzy Inference (QFI) based systems (prototype of Intelligent System of Systems Engineering). We stress our attention on the robustness features of intelligent control systems.*

Keywords: Robust Intelligent Control, Self-Organization, Quantum fuzzy inference, Quantum Computing, System of Systems Engineering

1. Introduction

For complex and ill-defined dynamic systems that are not easily controlled by traditional control systems (such as *P*-[*I*]-*D*-controllers) - especially in the presence of different stochastic noises - the System of Systems Engineering methodology provides fuzzy controllers (FC) as one of alternative way of control systems design [1]. Since their appearance, fuzzy controllers demonstrate their great applicability in cases when control object is ill-defined or it operates under unknown conditions, when traditional negative feedback based controller is failing [1, 2]. Soft computing methodologies [1], such as genetic algorithms (GA) and fuzzy neural networks (FNN) had expanded application areas of FC by adding learning and adaptation features. But still now it is difficult to design good and robust intelligent control system, when its operational conditions have to evolve dramatically (aging, sensor failure and so on). Such conditions could be predicted from one hand, but it is difficult to cover such situations by a single FC. One of the solutions seems obvious by preparation of a separate set of knowledge bases (KB-FC) for fixed conditions of control situations, but the following question raises: *how to judge which KB-FC should be operational in the concrete time moment*?

At this moment the most important decision is a selection of the generalization strategy which will switch the flow of control signals from different FC, and if necessary will modify their output to fit present control object conditions. For this purpose the simplest way is to use a kind of weighted aggregation of outputs of each independent FC, but this solution will fail and distribution of weighting factors should be somehow dynamically decided.

We propose a solution of such kind of generalization problems by introducing a *self-organization* design process of KB-FC that supported by the *Quantum Fuzzy Inference* (QFI) based on Quantum Soft Computing ideas [3].

Proposed QFI system consists of a few KB-FCs, each of which has prepared for appropriate conditions of control object and excitations by Soft Computing Optimizer. QFI system is a quantum algorithm block, which performs post processing of the results of fuzzy inference of each independent FC and produces the generalized control signal output. In this case the output of QFI is an optimal control signal, which combines best features of the each independent FC outputs. Therefore the operation area of such a control system can be expanded greatly as well as its robustness. Robustness of control signal is the background for support the reliability of control accuracy in uncertainty environments.

Main goal: In this report we give a brief introduction on soft computing tools for designing independent FC and then we will provide QFI methodology, and the simulation example of robust intelligent control based on QFI. The role of KB design based on QFI in the solution of System of Systems Engineering problems is also discussed.

2. Problem's formulation

Main problem in modern FC design is how to design and introduce robust KBs into control system for increasing *self-learning, self-adaptation and self-organizing capabilities* that enhance robustness of developed FC. The *learning* and *adaptation* aspects of FC's have always the interesting topic in advanced control theory and system of systems engineering.

These types of control quality can be achieved with SCO. For achieving of *self-organization* level in intelligent control system it is necessary to use QFI.

Figure 1 shows the interrelations between control quality measures and types of the computational intelligence tools.

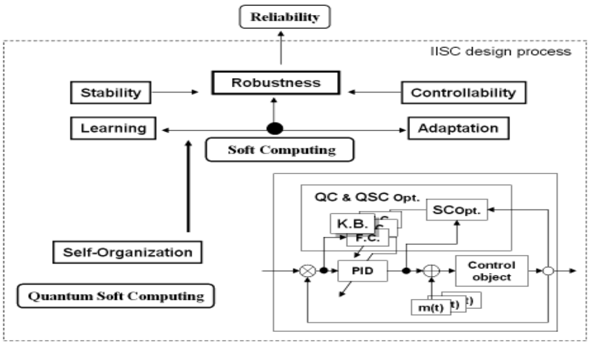

Figure1.Interrelations between control quality criteria

Many learning schemes were based on the *back-propagation* (BP) algorithm and its modifications (see, for example, [1] and their references). Adaptation processes are based on iterative stochastic algorithms. These ideas are successfully working if we perform our control task without a presence of ill-defined stochastic noises in environment or without a presence of unknown noises in sensors systems and control loop, and so on. For more complicated control situations learning and adaptation methods based on BP-algorithms or iterative stochastic algorithms do not guarantee the required robustness and accuracy of control. The solution of this problem based on Soft Computing Optimizer (SCO) was developed in [1]. The described *self-organizing* FC design method is based on special form of QFI that uses a few of partial KBs designed by SC Optimizer tools [1,2]. QFI uses the laws of quantum computing [3-5] and explores three main unitary operations: (i) super-position; (ii) entanglement (quantum correlations); and (iii) interference. The general structure of QFI block is shown in Figure 2.

According to quantum gate computation [4, 5], the logical union of a few KBs in one generalized space is realized with *superposition* operator; with *entanglement* operator (that can be described by different models of *quantum oracle*) a search of "successful" marked solution is formalized; and with *interference* operator we can extract "good" solutions together with classical *measurement* operations.

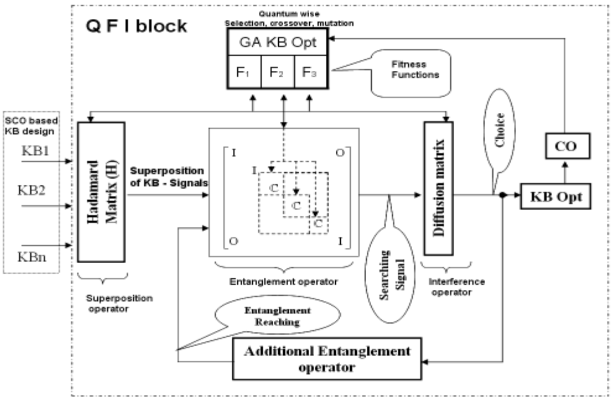

Figure 2. The structure of QFI block

The main technical purpose of QFI is to supply a self-organization capability for many (sometimes unpredicted) control situations based on a few KBs. QFI produces robust optimal control signal for the current control situation using a reducing procedure and compression of redundant information in KB's of individual FCs. Process of rejection and compression of redundant information in KB's uses the laws of quantum information theory. Decreasing of redundant information in KB-FC increases the robustness of control without loss of control quality as reliability of control accuracy. As a result, a few KB-FC with QFI can be adapted to unexpected change of external environments and to uncertainty in initial information.

Related works. In [5-8], ideas to use effective quantum algorithms in design of fuzzy systems are discussed. In [9-13], quantum optimization based on quantum genetic algorithm, quantum learning algorithms and quantum fuzzy neural network approach are considered. In this report we stress our attention on the main problem in System of Systems Engineering - the robustness features of intelligent control systems. For FC self-organizing capability support, we propose to use the *quantum fuzzy inference* based on a few KBs. We introduce main ideas of quantum computation and quantum information theory applied in developed QFI methods. *Quantum Fuzzy Inference* ideas are introduced. Robustness of new types of *self-organizing intelligent control systems* is demonstrated.

3. QFI based on quantum computing

For design of QFI based on a few KBs it is needed to apply the additional operations to partial KBs outputs that drawing and aggregate the value information from different KBs. Soft computing tool does not contain corresponding necessary operations [5]. The necessary unitary reversible operations are called as *superposition*, *entanglement* (quantum correlation) and *interference* that physically are operators of quantum computing [3-5].

In this report we introduce briefly the particularities of quantum computing and quantum information theory that are used in the quantum block (see, Figure 2) supporting a self-organizing capability of FC.

Quantum computing. In Hilbert space the superposition of classical states $\left(c_1^{(1)}|0\rangle + c_2^{(1)}|1\rangle\right)$ called quantum bit (qubit) means that "*False*" and "*True*" are jointed in one state with different probability amplitude, $c_i^1, i = 1,2$. If the Hadamard transform H is independently applied at different classical states then a tensor product of superposition states is the result:

$$|\psi\rangle = H^{\otimes n}|False\rangle = \frac{1}{\sqrt{2^n}} \otimes_{i=1}^{n} \left(|False\rangle + |True\rangle\right) \qquad (1)$$

The fundamental result of quantum computation stays that all of the computation can be embedded in a circuit, which nodes are the universal gates. These gates offer an expansion of unitary operator U that evolves the system in order to perform some computation. Thus, naturally two problems are discussed: (1) Given a set of functional points $S = \{(x,y)\}$ find the operator U such that $y = U \cdot x$; (2) Given a problem, find the quantum circuit that solves it. Algorithms for solving these problems may be implemented in a hardware quantum gate or in software as computer programs running on a classical computer [4, 5]. It is shown that in quantum computing the construction of a universal quantum simulator based on classical effective simulation is possible [4, 5].

Hence, a quantum gate approach can be used in a global optimization of Knowledge Base (KB) structures of intelligent control systems that are based on quantum computing and on a quantum genetic search algorithm (*QGSA*) [13].

Quantum information resources in QFI algorithm. Figure 3 shows the algorithm for coding, searching and extracting the value information from two KBs designed by SCO.

This algorithm use four Facts (see, Appendix) from quantum information theory: (i) compression of classical information by coding in computational basis $\{|0\rangle, |1\rangle\}$ and forming quantum correlation between different computational bases (Fact 1); (ii) separating and splitting total information on "classical" and "quantum" parts using Hadamard transform (Facts 2 and 3); (iii) extract unlocking information and residual redundant information by measuring the classical correlation in quantum state (Fact 4) using criteria of maximal corresponding amplitude probability. These facts are the informational resources of QFI background. Using these facts it is possible to extract additional amount of quantum value information from smart KBs produced by SC optimizer for design a *wise* control using compression and rejection procedures of the redundant information in a classical control signal.

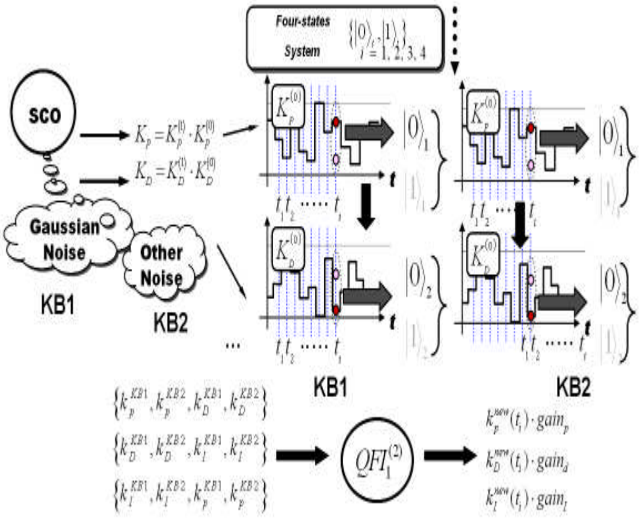

Figure 3. Algorithm structure of QFI

Below we discuss the application of this algorithm in QFI structure.

4. Design of self-organizing fuzzy controller's based on QFI

The kernel of the abovementioned FC design tools is a so-called SC Optimizer (SCO) implementing advanced soft computing ideas. SCO is considered as a new flexible tool for design of optimal structure and robust KBs of FC based on a chain of genetic algorithms (GAs) with information-thermodynamic criteria for KB optimization and advanced error back-propagation algorithm for KB refinement. Input to SCO can be some measured or simulated data (called as 'teaching signal" (TS)) about the modelling system. For TS design (or for GA fitness evaluation) we use stochastic simulation system based on the control object model. More detail description of SCO is given in [1, 2].

Figure 4 illustrates as an example the structure and main ideas of self-organized control system consisting of two FC's coupling in one *Quantum Fuzzy Inference* (QFI) chain that supplies self-organizing capability.

As above mentioned, QFI block (see, Figure 2) is based on three main quantum operators of quantum computing: superposition of classical states, entanglement, interference, and classical measurement. According to described above algorithm (see, Figure 3) the input to the QFI block is considered according Eq.(1) as a superposed quantum state $K_1(t)\otimes K_2(t)$, where $K_{1,2}(t)$ are the outputs from fuzzy controllers FC1 and FC2 designed by SC Optimizer for the given control task in different control situations (for example, in the presence of different stochastic noises).

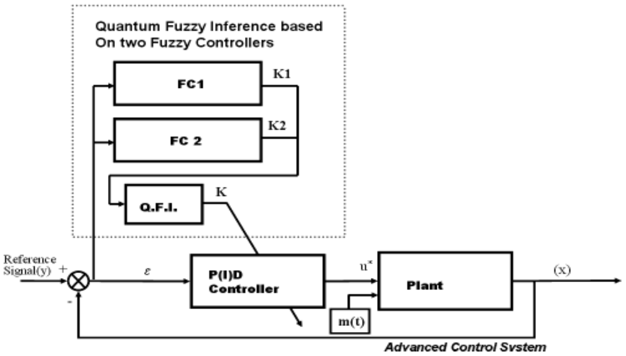

Figure 4. Main structure of intelligent self-organized control system

The algorithm of superposition calculation is presented in Figure 3 and described in [13]. Using the facts from quantum information theory (see Appendix) QFI extracts the value information from KB1 and KB2. In this case between KB1 and KB2 (from quantum information theory point of view) we organize communication channel using quantum correlations that is impossible in classical communication theory.

Let us now discuss the situation in which an arbitrary amount of correlation is unlocked with a one-way message.

Example. The initial state ρ is shared between subsystems held by *A* (KB1) and *B* (KB2), with respective dimensions d,

$$\rho=\frac{1}{2d}\sum_{k=0}^{d-1}\sum_{t=0}^{1}\left(|k\rangle\langle k|\otimes|t\rangle\langle t|\right)_A\otimes\left(U_t|k\rangle\langle k|U_t^{\dagger}\right)_B .$$

Here $U_0=I$ and U_1 changes the computational basis to a conjugate basis $\left|\langle i|U_1|k\rangle\right|=\frac{1}{\sqrt{d}}\quad\forall\, i,k$. In this case, *B* chooses $|k\rangle$ randomly from d states in two possible random bases, while A has complete knowledge on his state. The state ρ can arise from following scenario. Let us consider the communication process between two KBs as communication between two players *A* and *B* (see Figure 3) and let $d=2^n$. *A* picks a random n-bit string k and sends B $|k\rangle$ or $H^{\otimes n}|k\rangle$ depending on whether the random bit $t=0$ or 1. Here H is the Hadamard transform. A can send t to B to unlock the correlation later. Experimentally, the Hadamard transform and measurement on single qubits are sufficient to prepare the state ρ and later extract the unlocked correlation in ρ'. The initial correlation is small, $I_{Cl}^{(l)}(\rho)=\frac{1}{2}\log d$.

The final amount of information after the complete measurement M_A in one-way communication is as $I_{Cl}(\rho')=I_{Cl}^{(l)}(\rho)=\log d+1$, i.e., the amount of accessible information increase [14].

Therefore, using the Hadamard transformation and a quantum correlation as communication between a few KB's it is possible to increase initial information by quantum correlation.

In present report we consider a simplified case of QFI when with the Hadamard transform is organized an unlocked correlation in superposition of two KBs; the entanglement operation is modelled as quantum oracle that estimates a maximum of amplitude probability in corresponding superposition of classical states. Interference operator extracts this maximum of amplitudes probability with a classical measurement.

Below we discuss application of described QFI model to control of non-linear locally unstable dynamic system.

5. Benchmark simulations

Consider the following model of control object as nonlinear oscillator with sizable nonlinear dissipative components:

$$\ddot{x}+\left[2\beta+a\dot{x}^2+k_1x^2-1\right]\dot{x}+kx=u(t)+\xi(t), \qquad (2)$$

where $\xi(t)$ is a stochastic excitation with an appro-priate probability density function. The system, described by Eq.(2) appears different types of behaviour: if $\beta=0.5$ (other parameters, for example, $\alpha=0.3; k_1=0.2; k=5$), then dynamic system motion is asymptotically stable; if $\beta=-1$ (other parameters is the same as above), then the motion is locally unstable. Consider excited motion of the given dynamic system under fuzzy PID-control. Let the system be disturbed by a *Rayleigh* (*non Gaussian*) noise. Stochastic simulation of random excitations with appropriate probability density functions is based on nonlinear forming filters methodology developed in [1].

FC1 design. The following model parameters: $\beta = 0.5; \alpha = 0.3; k_1 = 0.2; k = 5$ and initial conditions [2.5] [0.1] are considered. Reference signal is: $x_{ref} = 0$. K-gains ranging area is [0,10]. By using SC Optimizer and teaching signal (TS) obtained by the stochastic simulation system with GA [1,2]) or from experimental data, we design KB of FC 1, which optimally approximate the given TS (from the chosen fitness function point of view).

FC2 design. The following *new* model parameters: $\beta = -1; \alpha = 0.3; k_1 = 0.2; k = 5$ are used. Initial conditions are the same: [2.5] [0.1]. ***New*** reference signal is: $x_{ref} = -1$. K-gains ranging area is [0,10].

We considered different control situations and compared control performances of FC1, FC2 and self-organized control system based on QFI with two FC's. In Table 1 four different control situations are described. Figures 5-7 show, as example, the comparison of FC1, FC2 and self-organized control system based on QFI for Environments 2 and 4.

Table 1

<u>Environment 1</u>: Rayleigh noise; Ref signal = 0; Model parameters: $\beta = 0.5; \alpha = 0.3;$ $k_1 = 0.2; k = 5$	<u>Environment 2</u>: Rayleigh noise; Ref signal = -1; Model parameters : $\beta = -1; \alpha = 0.3;$ $k_1 = 0.2; k = 5$
<u>Environment 3</u>: Gaussian noise; Ref signal = -0.5; Model parameters: $\beta = -1; \alpha = 0.3;$ $k_1 = 0.2; k = 5$	<u>Environment 4</u>: Gaussian noise; Ref signal = +0.5; Model parameters: $\beta = -1; \alpha = 0.3;$ $k_1 = 0.2; k = 5$

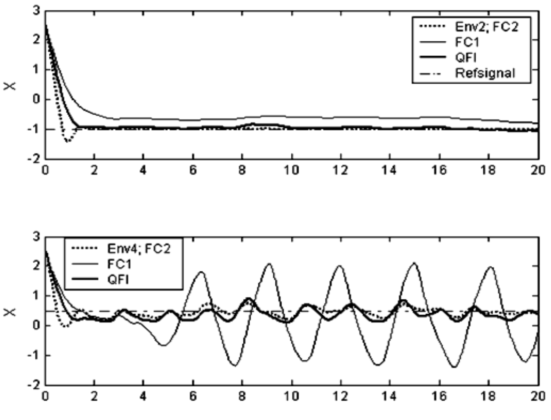

Figure 5. Motion under different types of control in two different environments

Simulation results show that QFI can organize optimal robust control signal from two KBs outputs with simple control laws of PID coefficients gains. In the case of Environment 4 FC1 loose robustness.

From game theory point of view we have *Parrondo* paradox: from two KBs that are not winner in different environments we can design with QFI one winner control signal. This effect was described also in [13].

6. Conclusions

1. SC Optimizer tool can realize allows us to model different versions of KBs of FC that guarantee robustness for fixed control environments.

2. The QFI block enhances robustness of fuzzy controllers using a self-organizing capability.

3. Designed FC based on QFI achieves the prescribed control objectives in many control situations.

4. Using SC Optimizer and QFI we can design *wise control* of essentially non-linear stable and, especially, of unstable dynamic systems in the presence of uncertain information about external excitations and in presence of changing reference signals (control goal), and model parameters.

5. QFI based FC requires minimum of initial information about external environments and internal structure of control object.

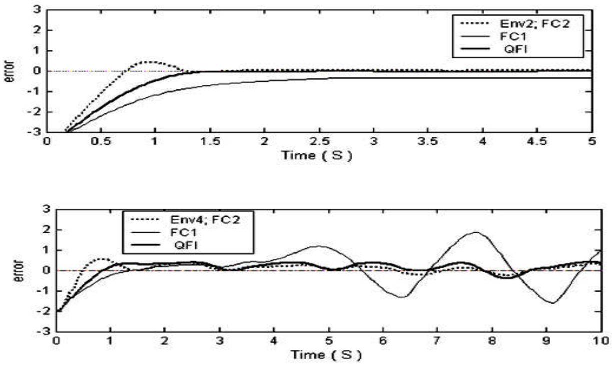

Figure 6. Control error in different types of control in two different environments

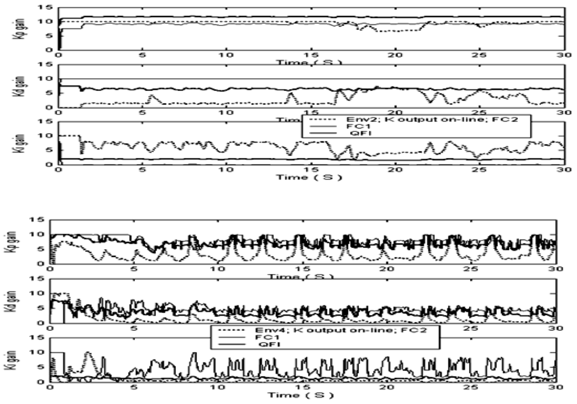

Figure 7. Control laws in different types of control in two different environments

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Appendix: *Quantum Information Processing***.** Quantum information theory has strict rules on how to extract information out of an unknown quantum state. Optimal drawing process of value information from a few KBs that are designed by soft computing is based on following four facts from quantum information theory: (*i*) the effective quantum data compression; (*ii*) the splitting of classical and quantum parts of information in quantum state; (*iii*) the total correlations in quantum state are "mixture" of classical and quantum correlations; and (*iv*) the exiting of hidden (locking) classical correlation in quantum state.

Let us briefly consider the physical meaning of these facts and its role in optimal control signal design.

Fact 1: *Quantum Data Compression*. Shannon has shown how much a message constructed from N independent letters (x_a), where each letter occurs with *a priori* probability p_a, can be compressed. Therefore, a block code of length NH^{sh} bits (where H^{sh} is Shannon entropy) encodes all typical sequences irrespective of how the atypical sequences are encoded and the probability of error will still be less than ε. In quantum information theory the letters are density matrices and one has to distinguish two cases, namely when the density matrices correspond to ensembles of q pure states, $|\phi_a\rangle$, or when they are formed from density matrices ρ_a, with probability p_a. The von Neumann entropy S of the message is simply related to the entropy of the ensemble, $S\left(\rho^{(N)}\right) = NS(\rho)$. It is well known that in general case $H(p) \geq S(\rho)$, i.e. the Shannon entropy is greater then von Neumann entropy [4].

It means that with quantum information approach it is possible to make more deep compression of classical value information.

Fact 2: *Splitting of information in a particular quantum state into classical and quantum part*. The classical information obtained by measuring of outcomes i with probabilities p_i is $H(p)$. If the quantum states ρ_B^i have support of orthogonal subspaces, then the entropy of the final state (after measurement) is the sum of the residual quantum entropy $\sum_i p_i S\left(\rho_B^i\right)$ and the classical information, i.e., $S\left(\sum_i p_i \rho_B^i\right) = \underbrace{H(p)}_{Classical} + \underbrace{\sum_i p_i S\left(\rho_B^i\right)}_{Quantum}$. We see then that the information in a quantum state may be split into a *quantum* and a *classical* part. Therefore, in our case we produce with SCO a classical part of information and the *deficit* of classical information is

$$\Delta I = S\left(\sum_i p_i \rho_B^i\right) - \underbrace{\sum_i p_i S\left(\rho_B^i\right)}_{Quantum} = \underbrace{H(p)}_{Classical} .$$

It means that it is possible to extract additional amount of quantum value information from smart KBs (produced by SC Optimizer) for design wise control using compression procedure with the rejection of the redundant information in classical control signal (using corresponding quantum correlation).

Fact 3: *Total, classical and quantum correlation amounts*. Entanglement, and correlations in general, are typical quantum resources. However, not all correlations have pure quantum nature. Generically, total correlations are “mixture” of classical and quantum correlations. An important issue is to know to what extent classical correlations are used in quantum algorithms. For example, if one is able to determine the classical part of correlations then by the optimal positive operator valued measurement (POVM) one can extract some information in classical form leaving the quantum state with less entropy. The total amount of correlation can be separated on “classical“ and “quantum” parts and is equal to the maximal classical/quantum mutual information $I(A:B)$, thus providing it with a direct operational interpretation.

Fact 4**:** *Hidden (locking) classical correlation in quantum state*. The surprising fact that incremental proportionality for $I_{Cl}(\rho) = \max_{M_A \otimes M_B} I(A:B)$ obtained by local measurements $M_A \otimes M_B$ on the state ρ_{AB} can be violated in some extreme manner for a mixed initial state ρ: a single classical bit, sent from A to B, can result in an arbitrary large increase in $I_{Cl}(\rho)$. This phenomenon can be viewed as a way of locking classical correlation in the quantum state ρ. Since incremental proportionality of $I_{Cl}(\rho)$ holds classically, the phenomenon of locked correlation is purely quantum effect. It is direct consequence of the indistinguishability of non-orthogonal quantum states. Therefore, there exist quantum bipartite states, which contain a large locked classical correlation that is unlocked by a disproportional small amount of classical communication. There are $(2n+1)$-qubit states for which a one-bit message doubles the optimal classical mutual information between measurement results on the subsystems, from $n/2$ bits to n bits. This phenomenon is impossible classically.

However, states exhibiting this behaviour *need not be entangled* and corresponding communication can be organized using Hadamard’s transform [14].