HOW TO TRANSMIT ARTIFICIAL INFORMATION IN PERIPHERAL NERVES WITHOUT DISTURBING THEIR NATURAL INFORMATION FLOW

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ABSTRACT
According to current knowledge information in human peripheral nerves is transmitted in frequency coded format. The number of action potentials per time instance carries the information in the axon. The frequency coded transmission happens with a very low rate compared to its theoretical capacity. This means that free capacity exists in the nerves. In this study the amount of pulse interval coded information, which could be embedded to the natural frequency coded information in axons without changing its information content, was evaluated with help of simulations. The simulations showed that attached to natural transmission there would flow even double amount of pulse interval coded information, parallel to the frequency coded information. In future there could be many useful applications of this capacity.

KEY WORDS
Axon, capacity, and simulation.

1. Introduction
In future more and more implantable devices are used to replace, boost or help many mechanical and physiological functions inside the human body. Their mutual communication could be arranged via biological nervous network. Compared to wires or RF-waves there are several benefits to use nerves, for example EMC-resistance, reliability and stability.

Information flow in human peripheral nervous system is coded to action potential trains in nerve fibres. The natural information coding method is frequency coding (FC), where the information is coded to the number of action potentials in the nerve per time period. For example, the contraction force of the muscle fibre is proportional to the number of action potentials per second [1-5].

However, in theory there are also two other possible methods to code information to the action potential trains: binary coding (BC) and pulse interval coding (PIC) [6,7]. In BC the information in the nerve is presented as ‘no action potential’ and ‘one action potential’ per time instance and in PIC the information is presented with the time intervals between consequent action potentials [7]. The information presentation in the PIC is conceptually different from the BC and FC methods.

The theoretical information transmission capacity of the nerves is rarely, perhaps never, used totally. For example, the theoretical information transmission capacity of a human peripheral nerve with maximum firing rate of 200 impulses per second is about 100 bit/s when FC is applied [5] but however the information transmission rate with a typical firing rate of a muscle (for example, in some cases roughly 5-50 impulses per second [8]) is only about 10 percent of that.

There is a lot of details like synaptic unreliability [9] or characteristics of sampling in estimation of entropy of action potential trains [10] which has an effect for the accurate estimation of information rates in nerves. One specifically interesting point in information transmission in peripheral nerves is that by embedding suitable pulse interval coding to the natural frequency coded action potential train it is possible to transfer more information by the action potential train which originally included frequency coding only. In other words, each frequency coded information symbol in the transmission consists of a known number of action potentials, and by giving meaning for the internal time distances between single action potentials inside the frequency coded symbol additional information can be transmitted. In this study characteristics of that kind of information transmission in a nerve was studied and simulated.

2. Methods

Frequency coding (FC) and pulse interval coding (PIC)
In FC the information is presented as a number of action potentials per time instance in the axon. Let us mark the time instance which is in use with $t_{\text{max}}$ and the minimum time interval between consecutive action potentials in axon (i.e. the inverse of maximum firing rate [1] of the axon) with $t_{\text{min}}$. In addition, let’s assume $t_{\text{max}}$ is also the longest time interval between consecutive action potentials in axon. Using this notation the largest number of action potentials per time instance $t_{\text{max}}$ is...
$t_{\text{max}}/t_{\text{min}}$ and the minimum number of action potentials is 1. With this coding scheme it is possible to send $t_{\text{max}}/t_{\text{min}}$ different symbols through the axon. The information theory [11] states if the symbol probability density of the sent signals in the information transmission is flat the information transmission rate is the highest. In this case the information transmission rate in FC is [6]

$$C(t_{\text{min}}, t_{\text{max}}) = \log_2 \left( \frac{t_{\text{max}}}{t_{\text{min}}} \right) \text{ bit/s.}$$  \hspace{1cm} (1)

In the reference [5] it is shown that the Equation (1) reaches its maximum when $t_{\text{min}}$ is as small as possible and $t_{\text{max}} = 3 \cdot t_{\text{min}}$. Thus, in FC the information transmission capacity is

$$C(t_{\text{min}}, 3 \cdot t_{\text{min}}) = \log_2 \left( \frac{3}{3 \cdot t_{\text{min}}} \right) \text{ bit/s.}$$  \hspace{1cm} (2)

On the other hand, in the PIC the information is put to the time intervals between consecutive action potentials. Let us use the same $t_{\text{min}}$ and $t_{\text{max}}$ notations as in FC case and in addition let’s determine $\Delta t$ represents the maximum accuracy one action potential can be determined in the axon. With this notation the number of possible symbols in the coding is $(t_{\text{max}} - t_{\text{min}})/\Delta t$. By assuming the symbols in coding represent flat probability distribution the information transmission rate is [5,7]

$$C(t_{\text{min}}, t_{\text{max}}, \Delta t) = \frac{2}{t_{\text{max}} - t_{\text{min}}} \log_2 \left( \frac{t_{\text{max}} - t_{\text{min}}}{\Delta t} \right) \text{ bit/s.}$$  \hspace{1cm} (3)

The Equation (3) reaches its maximum when $t_{\text{min}}$ and $\Delta t$ are as small as possible and the $t_{\text{max}}$ is selected in a way the equation [5,7]

$$\ln \left( \frac{t_{\text{max}} - t_{\text{min}}}{\Delta t} \right) = \frac{t_{\text{max}} + t_{\text{min}}}{t_{\text{max}} - t_{\text{min}}}$$

is true. A procedure to calculate a $t_{\text{max}}$ value which satisfies this requirement is presented in the reference [5] in detail. Let us mark this $t_{\text{max}}$ value as $t_{\text{result}}$. This results the PIC information transmission capacity

$$C(t_{\text{min}}, t_{\text{result}}, \Delta t) = \frac{2}{t_{\text{result}} - t_{\text{min}}} \log_2 \left( \frac{t_{\text{result}} - t_{\text{min}}}{\Delta t} \right) \text{ bit/s.}$$  \hspace{1cm} (4)

The information transmission capacities in FC and PIC are both dependent about the parameter $t_{\text{min}}$ but only the PIC is dependent about the parameter $\Delta t$. For example by assuming the $t_{\text{min}}$=5ms and $\Delta t$=1ms the maximum information transmission capacity is 106 bit/s for FC and 334 bit/s for PIC. In the reference [5] it is shown that PIC has always higher capacity than FC if $t_{\text{min}}/\Delta t$ is higher than about 0.7. Hence, from the information transmission capacity point of view always when $t_{\text{min}}$ is more than 70% of $\Delta t$ it would be more advantageous to transmit information using PIC instead of FC. However, the nature has built main principles for the information transmission in nerves on the FC principle and thus there are theoretical possibilities to transmit also additional information in form of PIC in the FC signal. Specially, the natural information transmission seems not to use all of the capacity of nerves. For example, the detected typical firing rates in the human peripheral nerves [8, 12] seem not to select $t_{\text{min}}$ and $t_{\text{max}}$ parameters in an optimal way.

**Concept of the frequency coded information manipulation**

In FC the receiver of the system determines the transmitted symbol on the basis of the number of action potentials per time instance whereas, in theory, the internal structure of the action potential pattern of one symbol has no effects to the result. In this study is developed the theoretical basis for an artificial manipulation method, which takes the frequency coded action potential signal from the axon and adds additional information in the PIC format to the signal by rearranging the single action potential occurrence instances in a way that the frequency coded information remains the same. The rearranged action potential stream is generated back to the axon. This rearrangement principle is exemplified in Figure 1, in which alternatives of PIC symbols of one FC symbols are shown.
In Figure 1 at top is shown an example of a FC symbol (4 action potentials per 300ms). Below this symbol is presented variants of this symbol, which each form one PIC symbol. Next, Figure 2 presents the whole concept. In this concept it is assumed that the nerve innervating the muscle is surrounded with an appropriate intelligent electrode system which has ability to embed additional information to the original nerve. The generation of new action potentials to the nerve is easy by electrical stimulation. The deletion of original action potentials in the axon is a slightly more complicated task. This could be done by generating an action potential running to the opposite direction than the original action potential. When the original and generated action potential collides, they vanish. This way the system could delete original action potentials and re-organize them to state the rearrangement of the action potential stream. Thus it would be possible to transfer information to artificial receiver which measures the nerve signal at the level of the muscle with a special electrode.

The $t_{\text{min}}$ and $t_{\max}$ parameters in FC state the basic constraints for the natural information transmission in the system. Let us mark the minimum possible time interval between consequent action potentials as $a_{\text{min}}$ and the applied coding parameters in FC as $t_{\text{min}}(t_{\text{min}} \geq a_{\text{min}})$ and $t_{\max}$. In this case there are $t_{\max}/t_{\text{min}}$ possible symbols in FC and except the first symbol (one action potential) it is possible to embed some additional information in the PIC format to them. The alternatives for the PIC transmission for each symbol including $K$ action potentials can be determined by the following numerical algorithm:

1. Determine all possible locations $N$ of action potentials during one frequency coded symbol.
2. Determine all possible combinations $\binom{N}{K}$ of the above determined locations.
3. Determine all combinations of the above which state the conditions of $t_{\text{min}} \geq a_{\text{min}}$. The number of passed combinations is the number of possible symbols of PIC in the case of studied frequency coded symbol.

Figure 3 exemplifies the number of alternative PIC symbols which are possible to embed to the FC symbols in case of $a_{\text{min}} = t_{\text{min}} = 5\text{ms}$, $t_{\max} = 25\text{ms}$ and $\Delta t = 1\text{ms}$.
Let us mark the number of possible PIC symbols in each FC symbol as \( S(t_{\text{min}}, t_{\text{max}}, \Delta t, a_{\text{min}}) \) where \( k \) is the number of action potentials in the FC symbol. By determining each PIC symbol equally probable the information transmission rate of the PIC part in the transmission is

\[
C_p = \frac{t_{\text{max}}}{\Delta t} \sum_{k=2}^{t_{\text{max}}/t_{\text{min}}} p(k) \log_2 \left( \frac{1}{S(t_{\text{min}}, t_{\text{max}}, \Delta t, a_{\text{min}}, k)} \right) \quad \text{bit/s} \quad (7)
\]

where \( p(k) \) is the probability of the symbol \( k \) in FC. The simultaneous FC transmission rate is

\[
C_f = \frac{\sum_{k=1}^{t_{\text{max}}/t_{\text{min}}} p(k) \log_2 (p(k))}{t_{\text{max}}} \quad \text{bit/s}. \quad (8)
\]

By using the above presented notations the manipulator block in the Figure 2 can be presented as shown in Figure 4.

3. Results

The information transmission was simulated with Matlab® software [13]. First the information transmission was simulated with different kind of transmission properties and then the possible PIC capacity was estimated with the information transmission properties occurring in the natural information transmission in the human body.

First the transmission rate of parameters \( a_{\text{min}} \), \( t_{\text{min}} \), \( t_{\text{max}} \) and \( \Delta t \) parameters were investigated. The probabilities \( p(k) \) were determined to be always equal. Figure 5 presents the FC and PIC information transmission rates as a function of \( t_{\text{max}} \) with \( a_{\text{min}} = t_{\text{min}} = \Delta t = 5\text{ms} \).

In Figure 5 it is seen that the ‘space’ for the PIC transmission increases due the \( t_{\text{max}} \) increases. However, the sum of the FC and PIC information rate remains roughly the same along the \( t_{\text{max}} \) axis.

Next, to estimate the information transmission rates in natural case in human peripheral nervous system simulations were done with fixed parameters. A good estimate for the typical \( a_{\text{min}} \) in the human peripheral nervous system is 5ms [5] and the typical firing rate of muscles may be roughly between 5 and 50 [8] impulses per second meaning \( t_{\text{min}} = 20\text{ms} \) and \( t_{\text{max}} = 200\text{ms} \). Figure 6 presents the information transmission rates with those parameter selections as a function of \( \Delta t \).
capacity. Further, PIC capacity rises rapidly with smaller
PIC capacity is almost double the corresponding FC

in muscle activation there are two basic ways to control
steering of the periphery would be done by the PIC? Or,
by the nerve activity [14]. Who knows if that kind of
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information is never transmitted in PIC format in the
amount of PIC information which could exist in natural

determines two important things. First, it states the
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established with a system presented in Figure 2

4. Conclusion

The information transmission capacity which could be
established with a system presented in Figure 2 determines two important things. First, it states the
amount of PIC information which could exist in natural
format in the nervous system. Namely, we are not sure
that information is never transmitted in PIC format in the
peripheral nervous system. For example, there is strong
evidence that the muscle phenotype is controlled partially
by the nerve activity [14]. Who knows if that kind of
steering of the periphery would be done by the PIC? Or,
in muscle activation there are two basic ways to control
the muscle contraction: recruitment and firing rate. For
example, in the reference [8] it is shown that the firing
rate varies due to the number of recruited fibres. Hence,
theoretically it would be possible at the entity level that
the CNS reduces the firing rate of some fibres during
some function on-fly to make it possible to transmit some
important information in PIC format. Further, in some
muscular movements the exact timing is important. In
those cases it is evident that the timing or time intervals in
the nerve signals has at least some important role in the
information transmission in peripheral nerves. Second, the
information transmission capacity determines the amount
of information which could be transmitted if some special
artificial function should be implemented to the peripheral
nervous system. For example, by applying the concept
presented in Figure 2 it would be possible to transmit
blood pressure information from artery from wrist via the
afferent nerves running in the arm to a cardiac pacemaker
locating in the thorax area. Efferent nerves could be used
when information is transmitted from body are to hands
or legs.

The simulations presented in this study shows
that in theory it might be possible that in the peripheral
nervous system is transferred even double amount of
information with using PIC (Figure 6) instead of FC. The
theoretical reason for so high possibility to increase the
information rate is that in natural transmission the FC
parameters are not selected ‘strictly’ (Figure 5). The
capacity estimates above were done by making rough
estimates of the axon properties and thus to obtain more
accurate results in future studies the manipulator block
presented in Figure 4 should be implemented
experimentally in vivo tests.

At general level, it would be possible that the
information transmission in human peripheral nervous
system has two possible modes, FC and PIC, and the
relative amount of information flow in those varies
depending on the situation. If so, this would be one reason
for the fact that the FC transmission in the human body
seems to function with a very low rate when compared to
the theoretical capacity.

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