Neuro-inspired Quantum Nets: a Proposal

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Abstract

Through this research we wish to build novel bio-inspired quantum networks which exhibit a form of learning and adaptation. These can benefit society by being more nimble and resilient to ecosystem changes than their traditional counterparts. This research proposal is divided into three research themes, which are integrated towards the end.

1 Decoherence, Noise and Metric Perturbations

Decoherence is the decay of the 'quantum-ness' of a quantum system due to environmental interactions. Any quantum information bearing system, say a qubit, that we transport via a quantum network is susceptible to decoherence.

Noise, on the other hand, also creates a decay in the decode-ability of the transmitted random variable in a communication system. This makes noise an important consideration in the models of classical-quantum channels which are part of any quantum network.

Finally, metric perturbations are disturbances in the metric of spacetime that can interact with physical systems and either convey information, or create a modification that is unwanted. Quantum control is currently used in the detection of gravitational waves. If and when these detectors become wired with quantum networks, these networks will need to carry some information regarding metric perturbations as well, making a joint study relevant.

Additionally, there are a lot of orthogonal open problems in all these three areas. Decoherence itself is a poorly understood quantum phenomenon. Its ramifications for biology are also largely unexplored.

Noise in communication systems, both classical and quantum has several open problems. For example, we recently modeled a Gaussian channel with Brownian noise, but an open problem that immediately suggests itself is to look at Brownian noise with drift. This may have implications for the field of finance and economics.

Similarly, the field of gravitational waves or metric perturbations has recently flowered due to actual detection of such waves in the laboratory. Several new types of detectors and other applications are in the works and require further development.

1.1 Contributions

1.1.1 Decoherence

We recently proposed [1] a mechanism for universal quantum computation in the brain, that recognizes the process of decoherence taking place at the ion channel level at nodes of Ranvier, and incorporates it into the multi-stage scheme of computation and information processing in the axons of a brain.

1.1.2 Noise

We recently showed [2] an upper bound on the reliability function of a Gaussian communication scheme for which we had a lower bound already [3]. The two bounds match under certain parameter regimes.

1.1.3 Metric Perturbations

We recently showed [4] the impact of metric perturbations on bona-fide neural (bio-physical) systems. The impact is small and perhaps beyond current measurement technological abilities, but is nevertheless present.

2 Computation and Information Processing

Computation is the performance of a meaningful mathematical action, an action that is suggestive, actionable or informative. When a quantum algorithm performs a Grover search on a set of inputs, the results are meaningful to the user.

Information processing is a specific type of computational work where the constituent components are stochastic, or probabilistic in nature. When a quantum source emitting qubits is to be sent over a quantum medium such as a network, the task involves manipulation and transformation of the probabilistic-ally structured object(s).

Computation and information processing suggest a lot of open problems when seen in relation to neuroscience. How does the brain perform its actions in the world on the basis of stimuli received, is a computational question. First of all, mathematical operations are involved, such as the thresholding and production of neural signals, governed by precise dynamical laws and inter-relations. On top of this, the mathematical actions have meaning since they govern the life of the organism involved. Even seen merely as an information processing, neural communication is a wide field for advancing our understanding of *fundamental limits* in the neural context.

2.1 Contributions

2.1.1 Computation

In [5], we provided a geometric picture of the synchronization taking place in a tract of neural axons. Here the computation involved was primarily an inner product between two signals and the result was meaningful since it led to synchronization which we had shown previously to be a mechanism for selective amplification of stimuli presented to the tract [6].

2.1.2 Information Processing

In [7, 8], we computed the information bearing capacity of a tract of neural axons under variations of the geometry of the tract. This involved discretizing the input space and treating the tract as a memory-less discrete channel whose capacity can be found using the standard Blahut-Arimoto algorithm.

3 Networks and Learning

Networks come in two varieties - natural and man-made. Under the man-made category, 5G-6G and beyond technologies are currently being implemented for mobile wireless communication. These technologies face fundamental challenges across time and space which are addressed in different ways in each successive iteration. This category also includes neural networks.

Under the natural category come the networks of synchronizing neurons in the nervous system. Synchronization in these networks allows the performance of many computations and distribution of results in parallel within relatively short temporal durations.

The wider adoption of 5G and 6G and related technologies only puts more strain on researchers to develop even better performing strategies to deal with evolving problems and the frontier continuously unfolds and expands.

Similarly, as our understanding of neuromolecular processing, synaptic signaling, potentiation and other fundamental neurobiological processes improves, the understanding of networks in the brain will also need to keep abreast, accounting for this additional data.

3.1 Contributions

3.1.1 Networks

We have recently proposed [9] a network coding view of ephaptic synchronization in the brain which shows how data may be actually exchanged in ephaptic coupling. We have similarly proposed a role for the ephapse in the brain which is on par with that of the synapse [10].

Networks in the brain can also be formed between regions devoted to differing functionalities, such as the auditory and visual regions. In a highly cited paper we showed that integration of the information in these regions is actually related to the perception of a psycho-physical illusion which can be measured in the laboratory [11]. We have related this integration to ephaptic coupling in a recent work [12].

3.1.2 Learning

In work that is in preparation, We have proposed a modification of the fundamental perceptron algorithm of Rosenblatt to incorporate branching, geometry and ephaptic coupling. The novel algorithm is being applied to a problem of 5G security.

4 Succinct Research Goal and Methodology

4.1 Goal

Neurobiologically-inspired quantum networks at the physical and application layer: theory, simulations and implementation.

4.2 Methodology

Identification of key processes taking place in a given setting. Design of variations and interventions to meet objectives, followed by in-depth analysis using mathematical tools.

5 Research Proposal

5.1 Short-term Proposal

Taking inspiration from our work in [9, 10] and [12], network coding, ephaptic synchronization and cross-modal integration could be linked. This can be accomplished in the 1 to 2 year horizon.

5.2 Long-term Proposal

In [1], we showed that the brain can act like a quantum computer. Over the longer term (5-10 years) the challenge before us is to determine the exact nature of this quantum computation in the brain. Can we pin-point the exact quantum algorithms that the brain is using for communication, computation and information processing? If so, can we build quantum networks that mimic the neurobiology? It is anticipated that these networks will be smart in the sense of energy-efficiency. Furthermore, the peripheral computation happening at their nodes can also be neurobiologically-inspired and therefore tap into the efficiencies of machine learning (as studied in quantum machine learning). Our principal tools will remain a mixture of theory, simulations and experimental implementations. We will work primarily in the quantum optical setting since there is a vast literature to support quantum optics experiments. Online courses such as those on Coursera will be used to augment our knowledge of the experimental domain. We will also leverage a network of quantum optics experts to provide inputs and guidance.

In order to answer the first question, it is proposed to have a precise mathematical version of [1] using the tools of Kraus operators [13] with metric perturbation-controlled unitaries performing the quantum computation. With the exact equations of the input and output in hand, we can predict probabilities of various observations and statistically combine large numbers of these outcomes to determine what would be macroscopically observable. This could then be compared with focussed neuroscientific experiments, possibly via optogenetics. For the second question, once the distributed/single-node nature of the algorithms is determined, optical quantum networks can be designed with the standard elements such as beam-splitters and mirrors so as to perform these brain quantum computations on a macro-scale. This will help to determine or further refine the exact nature of the processing. Potential gains from this investigation will be to society in the form of large-scale secure communication that is also good at adaptation and learning.

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