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Communication of uncoded sensor measurements through nanoscale binary-node stochastic pooling networks

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ABSTRACT

In recent work we defined a concept referred to as *stochastic pooling networks*, to describe a class of network structures in which various unexpected emergent features have been observed. Examples of stochastic pooling networks can be found in a diverse range of scientific and engineering contexts, as well as across a vast range of scales, ranging from macroscopic social networks to nanoscale electronics. Here we discuss the relevance of the stochastic pooling network concept to the design of communication and sensing networks at the nanoscale. The information theoretic limits to the performance of such networks when employed to communicate sensor measurements are analysed, and shown to compare favorably with the best possible choice of communication scheme. Optimization of the network in the presence of noise finds that a partially homogeneous network improves performance, and thus suggests an approach to simplifying the design of nanoscale analog-to-digital converters and sensor networks.

1. Introduction

1.1. Stochastic pooling networks

Stochastic pooling networks (SPN), as defined in [39]—see also [62]—are networks with the following properties:

> 'Multiple parallel noisy and compressed sensor measurements of a common input signal are combined into a single measurement by a physical channel, in such a way that pooling of measurements causes no (or negligible) further loss of information about the network's input signal, when compared with the best performance that could be achieved if all sensor measurements were available.'

This definition provides a clear distinction from many other kinds of networks, in that communication is directed from a single source common to all nodes in a sensor network, towards a single receiver. It is therefore similar to the 'refining sensor network' and unlike the 'expanding sensor network' concepts defined in [12]. On the other hand, this definition is rather broad in the sense that it can apply both to sensor networks and communication channels. The blurring of the distinction between sensing and communication is also central to the discussion in [12].

In contrast with [12], the idea of a *stochastic pooling network* originated from models of biological neuronal populations [57–59]. There were therefore dual reasons for defining the concept:

(1) as a model useful for explaining and predicting principles underpinning computation in biological brains ('neural coding');

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(2) as a potentially useful design aid for engineered sensor networks (both biologically-inspired [34], and otherwise).

The material in [39] was primarily focused on surprising emergent properties that arise in networks that combine the presence of random noise with lossy compression and redundancy. In particular, we demonstrated that pooling operations in SPNs can provide an optimal (or close to optimal) fusion of measurements. Here we have a different focus: the possible application of SPNs as a model for nanoscale communication. The theory we discuss is most relevant to the sensor end of the network. In [39] it was instead the pooling end.

1.2. Stochastic pooling networks and nanoscale communication/electronics

One of the scenarios for which the SPN construct provides a good model is that of nanoscale electronics [39]. For example, the model first considered in [57] has provided inspiration for novel reliability schemes in nanoscale logic gates [31,32]. Since all nanoscale communication networks will be made up of nanoscale devices, insights into the behaviour of networks of this type can be gained from design issues relevant to nanoscale electronics research, as we now discuss.

1.2.1. Robustness to noise

A crucial element for nanoscale electronics and devices, and one that is integral to the notion of SPNs, is design and function in the presence of significant levels of random noise.

One fundamental aspect that all nano-scale systems will have to overcome is a high level of intrinsic system noise and variability [4,55]. In general, as devices shrink in size, noise levels increase. The increase in noise occurs for a variety of reasons such as mesoscopic effects, constrained power dissipation and rescaling of parameters. Indeed, the noise problem is likely to be so acute that in some nano-devices signal-to-noise ratios (SNRs) of order 0 dB are predicted [42].

Mesoscopic effects arise due to thermal agitation and the discrete nature of matter which, on the nanoscale, becomes important [5]. The individual atomic or molecular fluctuations that accompany signal coding and transmission no longer average out as they tend to do in macroscopic systems. A well-known example of such an effect is shot noise but even thermal noise can become problematic at the nanoscale [22]. Such effects are well documented in studies of biological signals. For example, the release of neurotransmitter molecules in chemical synapses takes on a statistical character not too dissimilar to shot noise [23]. Additionally, Hooge's law [20] states that excess noise ($1/f$ noise) scales inversely proportionally to the number of charge carriers and this has been demonstrated in a wide range of devices (including neurons) [20]. Consequently, reducing the size of devices leads to an increase in $1/f$ noise.

Noise will also rise due to power constraints. Power dissipation will be constrained in nanoscale systems due to increased packing densities and limited available power. Furthermore, future nano-devices may well make use of scavenged power extracted from the ambient environment [49]. Such devices are likely to be limited to the ultra-low power regime and hence signal levels are again likely to also be strongly constrained with respect to the noise.

An example of how rescaling effects can lead to decreased SNR is demonstrated by MOSFETs. Reducing the size of MOSFETs leads to a reduction in the gate capacitance, and this enables faster switching. But, this also increases the bandwidth of the device and hence leads to an increase in thermal noise power. Indeed, such an effect is predicted to result in the 'death of Moore's Law' because of random bit flips [22].

Working with these levels of noise is going to challenge traditional engineering methods [4,25,26], and means new techniques are needed to improve reliability, such as the exploitation of noise [1,14,25] and use of SPN-like arrays [32]. As discussed in this paper, methods that do not explicitly take into account intrinsic system fluctuations will lead to suboptimal coding and transmission of signals.

1.2.2. Reliability and implementation difficulties at the nanoscale

Fault-tolerant architectures will be essential for nanoscale communication networks, due to the reduced reliability of components. The standard way of dealing with device failure (or intermittent device operation) is to build in redundancy. In this respect, a system that is actually designed as an SPN offers a potentially fault tolerant architecture [32].

Also, it is possible that connectivity between devices may be a problem at the nanoscale, i.e. it may not be possible to simply use wires, or 'wire equivalents'. For example diffusion has been proposed as a possible method of molecular communication [48]. In such systems, cross-talk between channels may be unavoidable and it is possible, therefore, that signal fusion via additive pooling is unavoidable or even desirable, because it will be easier to implement than other methods. This is similar to biological synapses. These use diffusion based communication, where the probability of a neuron producing the voltage pulses known as 'spikes' is dependent on the total *pooled* amount of neurotransmitter received.

Traditional coding of sensor information sources may be difficult to implement with rather crude nano-components. For example, even if source/channel separation is theoretically applicable and optimal [60], the algorithmic complexity needed to achieve it may mean it is difficult to implement with unreliable nanoscale components that have badly characterised properties.

In this sense, it may be that simpler coding methods may result in more reliable and easier to implement systems. In the SPN considered in this paper, the sensor nodes are binary. Such binary nodes may be desirable from this perspective because if we cannot produce well controlled binary signals then there is no chance of implementing well controlled analog or multistate signals.

For example, it may be very difficult (and wasteful) to develop reliable analog-to-digital converters at the nanoscale—if this is the case it would limit significantly the