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Networks of Biosensors: Decentralized Activation and Social Learning

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This paper deals with the dynamics of biosensors and networks of biosensors, where individual biosensors are constructed out of protein molecules. Such biosensors are fully functioning nano-machines. The paper explores methods for decentralized self-activation of networks of biosensors using game-theoretic methods. A global game analysis in terms of a Bayesian game, and a correlated equilibrium analysis is carried out. Also an example of change detection using quickest time detection with social learning is presented. The unifying theme is to understand how local decisions affect global decision making in a multi-agent system.

Keywords: Biosensors, ion channels, sensor network, social learning, global game

Biological ion channels are water-filled sub-nano-sized pores formed by protein molecules in the membranes of all living cells [13, 24]. Ion channels in cell membranes play a crucial role in living organisms. They selectively regulate the flow of ions into and out of a cell and regulate the cell's biochemical activities. In the past few years, there have been enormous strides in understanding of the structure-function relationships in biological ion channels due to the combined efforts of experimental and computational biophysicists [13, 29]. Such advances have facilitated the development of biosensors [15, 34, 35] that exploit the selective conductivity of ion channels. Such ion-channel based biosensors can detect target molecular species of interest across a wide range of applications. These include medical diagnostics, environmental monitoring and general bio-hazard detection.

By using such ion-channel biosensors as an example,[1] this paper deals with three questions involving sensor networks:

1. How can the dynamics of individual biosensors be modelled? The original works that deal with the construction of the ion-channel biosensor are [14–16, 53]. These ion-channel biosensors are built using gramicidin A channels (which was one of the first antibiotics isolated in the 1940s) imbedded into a synthetic cell membrane. Since the gramicidin channels move (diffuse) randomly in the outer membrane of the ion channel biosensor, we can also view the biosensor as a fully functioning nano-machine with moving parts. We refer the reader to [48] for an interesting overview of the interface between molecular biology (ion channels) and microelectronics.
2. Given a network of biosensors, how can individual sensors activate themselves in a decentralized fashion?

   To answer this question, we develop two approaches.

   (i) First we develop a game theoretic analysis of sensor activation algorithms that can be deployed by each biosensor. By using the theory of global

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[1] Similar techniques can be used for unattended ground sensor networks as described in [33] and body-area networks [11]

games, it is shown that simple threshold policies at each sensor achieve a symmetric Bayesian Nash equilibrium. The theory of global games was first introduced in [8] as a tool for refining equilibria in economic game theory, see [45] for an excellent exposition, and have subsequently been used to model speculative currency attacks. Global games form an ideal tool for decentralized coordination of sensors, see [27]. In dense sensor networks (i.e. where a large number of sensors are present), is natural to respond to the *decentralized awareness* of a sensor network with *decentralized information processing* for proper operation. The idea is that if each sensor or small group of biosensors can appropriately adapt their behavior to locally observed conditions, they can quickly self-organize into a functioning network, eliminating the need for difficult and costly centralized control.

(ii) We present stochastic approximation algorithms based on game-theoretic learning. Since centralized sensor coordination is a costly and complex process, we take a decentralized approach by equipping each sensor as an independent, non-linear adaptive filter, which optimizes sensor performance through a utility function, to trade off the energy cost of acquiring data against its value. The adaptive filters/stochastic approximation algorithms control local functionality only, with minimal message passing, thereby reducing inter-sensor communication and associated energy costs. This decentralized approach is attractive because it facilitates self-configuration of sensors, which allows for fast deployment as well as network robustness and scalability. Self configuration is achieved by the standard approach of improving filter performance based on time-averaged feedback. We refer the reader to [33, 44] for applications in sensor networks and spectrum sensing in cognitive radio. The algorithms are based on the work of [20, 21] which have been nicely analyzed using differential inclusions in [6].

3. How can biosensors learn from decisions made by other biosensors in a network?

This question is formulated as a sequential detection problem involving social learning. Section 4 presents two examples of stopping time problems involving social learning amongst multiple agents. We consider: How do local decisions in social learning affect the global decision in a stopping time problem? Social learning has been used in economics [5, 7, 9], for example to model behavior in financial markets; see also [40, 50]. In social learning, each agent optimizes its local utility selfishly and then broadcasts its action. Subsequent agents then use their private observation together with the actions of previous agents to learn an underlying state.

We consider a multi-agent Bayesian stopping time problem where agents perform greedy social learning and reveal their local actions to subsequent agents. How can the multi-agent system make a global decision when to stop? Such problems arise in automated decision systems (e.g., sensor networks) where agents make local decisions and reveal these local decisions to subsequent agents. Theorem 4.2 shows that the optimal decision policy of the stopping time problem has multiple thresholds. This is unusual: if it is optimal to declare state 1 based on a Bayesian belief, it may not be optimal to declare state 1 when the belief about work [28].

Organization

Fig.1 gives a schematic of the logical organization of this paper. Each box in Figure 1 demarcated in broken lines denotes a biosensor unit with a signal processing and control unit.

Section 1 begins with modeling each individual functional unit within the biosensor unit We model the individual ion channel biosensor as a second order linear system. Then we formulate the dynamics of the biosensor response to analyte. The presence of analyte decreases the admittance of the biosensor. In [30], an input controller was designed to optimize the input excitation to the biosensor to minimize the covariance of the biosensor impedance (see Fig. 1).

The rest of the paper considers a network of several biosensors – the figure shows two such biosensors for illustrative purposes. Section 2 uses the theory of global games to analyse simple threshold policies for sensor activation. Section 3 presents stochastic approximation algorithms for sensor activation such that the global behavior converges to a correlated equilibrium. Finally, Section 4 presents a social learning analysis of sequential detection when individual biosensors send their local decision to subsequent biosensors.

Finally, we note that literature in all the above sub-areas is extensive. Due to page restrictions, we refer the reader to [27, 28, 33–35, 44] for detailed literature surveys. In fact, as is often the case, many of the analysis tools here are developed from "old problems" which have become fashionable again. Game theoretic analysis of decentralized problems in sensor networks is becoming increasingly common; see [38, 41, 42]. There has been much recent research in energy saving mechanisms for sensor networks [10–12, 43, 51].