Cognitive Molecular Communication

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***Abstract*—A key requirement of molecular communication systems in many complex environments is that they should not disrupt the function of pre-existing biochemical systems; that is, the systems should *coexist*. In this paper, we develop a general framework for the coexistence problem by drawing an analogy to the cognitive radio problem in wireless communication systems. For the particularly promising *underlay* strategy, we propose a formalization and outline key consequences.**

I. Introduction

Some of the most ambitious proposals for the use of molecular communications are in complex environments, such as biochemical systems in the human body. In these environments, it is not only necessary for the molecular communciation system to work reliably, but also for the biochemical system to retain its function. That is, the molecular communication system and the biochemical system can *coexist*. In order to achieve this, the molecular communication system must be aware of its environment and be able to adapt its communication strategy.

At present, a framework is not available to establish when a molecular communication system and a biochemical system can coexist. A key difficulty is the fact that biochemical systems are governed by reaction-diffusion dynamics. These dynamics are described by systems of differential equations, which means that standard information and communication theoretic tools are not straightforward to apply. As such, it is challenging to determine the fundamental limits of the molecular communication system subject to constraints imposed by the presence of the biochemical system.

Nevertheless, the general problem of coexistence in molecular communication system bears strong analogies to coexistence in wireless communications, which has been addressed by the cognitive radio framework [1]. In cognitive radio, a secondary wireless communication network aims to access spectrum that is licensed to a primary wireless network without degrading the performance of the primary network. An analogy between coexistence in molecular communications and cognitive radio is highly desirable due to the well-developed toolbox for cognitive radio.

In particular, in the problem of coexistence in molecular communications, it is possible to identify the biochemical system with the primary network, while the molecular communication link can be identified with the secondary network. As such, fundamental strategies in cognitive radio can be adapted to molecular communications. This leads to the notion of *cognitive molecular communications*.

In this paper, we develop the analogy between coexistence in molecular communications and each of the three basic strategies in cognitive radio problem; namely overlay, underlay and interweaving. A key observation is that an important challenge is to establish the impact of a molecular communication link on a biochemical system, particularly for the underlay strategy. To this end, we outline our proposal in [2] to address this challenge.

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II. Cognitive Strategies

In cognitive radio, there are three basic strategies—underlay, overlay and interweaving—to allow a wireless network to access spectrum that has already been allocated to an existing wireless network without significantly degrading performance [3]. In this section, we propose that similar strategies are also available for the coexistence problem in molecular communications and identify scenarios where each strategy is applicable.

The basis for the analogy between cognitive radio and the molecular communications coexistence problem is that both the molecular communication system and the biochemical system exchange mass due to reactions between chemical species in each system. They also exchange information, either through dedicated reaction pathways or indirectly through observations made locally in the molecular communication system. A similar situation occurs in cognitive radio, except instead of the exchange of matter, the interaction is through electromagnetic interference.

The first strategy is *underlay*, where cooperation is not possible but the molecular communication system has knowledge of its impact on the biochemical system. The impact of the molecular communication system is determined by any changes to the dynamics of the biochemical system. More precisely, this impact can be formalized as changes to initial conditions or parameters of the differential equations describing the reaction-diffusion dynamics of the biochemical system. The underlay strategy is necessary when the information molecules used for the molecular communication link either overlap or react with the species in the biochemical system. In the case where the biochemical system is complex—i.e., containing a very large number of species—this situation is likely to occur and therefore it is important to design the molecular communication link to ensure the concentration of species in the biochemical system are not significantly perturbed.

The second strategy is *overlay*. In the context of cognitive radio, the overlay strategy is applicable when the secondary transmitting device has knowledge of the codebook and messages of transmissions in the primary network. That is, a high level of side information is available to the secondary network. The analogous setting in molecular communications is when the molecular communication link and the biochemical system are jointly designed.

Such a joint design can be developed in biochemical systems regulated by DNA transcription. In particular, if the transcription process is modified so that the production of information molecules is a by-product of existing chemical reactions, then there is no loss in the function of the biochemical system. A key example of this situation occurs in bacteria colonies such as *Vibrio fischeri* or *Vibrio herveyi*, where a dedicated communication link is established between bacteria, which is supported by the production of autoinducer molecules during the DNA transcription process [4].

The third strategy is *interweaving*. In cognitive radio, this strategy ensures that the secondary network does not interfere with the primary network by detecting spectrum holes. That is, no side information assumptions are required at the cost of additional signal processing to detect whether there is a primary network transmission on a given band at a given time.

In molecular communications, the analogous situation is when the information molecules do not react with any species in the biochemical system. In this case the molecular communication link can be viewed as an isolated chemical system, able to coexist with the biochemical system. This is an assumption widely used in existing communication and information theoretic studies, e.g., [5]. Nevertheless, it may be challenging to implement unless the dynamics of the biochemical system are very slow.

III. Coexistence via Underlay

Due to its limited requirements, the underlay strategy is particularly attractive. A key question in order to implement underlay methods is how to characterize the impact of a molecular communication system on a biochemical system. At present, there is not a general answer to this question. Nevertheless for the class of reaction-limited systems [2], [6], we have recently proposed an approach based on chemical reaction networks. Formally, in order to model biochemical systems as chemical reaction networks, the system is viewed as a tuple $(\mathcal{S}, \mathcal{R}, k)$ consisting of a set of chemical species, denoted by $\mathcal{S}$, that are related by a set of chemical reactions, denoted by $\mathcal{R}$, occuring at rates governed by a rate function k. As such, the building blocks are the chemical species in the system and the possible reactions between each subset of species.

Under mass action kinetics [7] and certain conditions on the biochemical system that guarantee the existence of a unique equilibrium, we have established the following result. For full details, see [2].

Theorem 1. *Let $(\mathcal{S}, \mathcal{R}, k)$ be a weakly reversible complex balanced reaction system with point of complex balance α. Suppose that for the trajectory $\mathbf{x}(t)$ with initial conditions $\mathbf{x}(0) \in (\mathbf{u} + H) \cap \mathbb{R}^{\mathcal{S}}_{\geq 0}$, the following limit holds*

$$\lim_{t \to \infty} \mathbf{x}(t) = \alpha. \tag{1}$$

Further, let $(\mathcal{S}_I, \mathcal{R}_I, k_I)$ be the reaction system corresponding to a molecular communication link. Suppose that reactions involving species in $\mathcal{S}$ and $\mathcal{S}_I$ are of the form

$$\sum_j b_j I_j + \sum_j c_j X_j \leftrightarrows \sum_j d_j X_j, \tag{2}$$

where at least one element of each set $\{b_j\}, \{c_j\}, \{d_j\}$ is strictly positive. Then, for any initial conditions $\mathbf{u} \in \mathbb{R}^{\mathcal{S}}_{>0}$, there exists a unique equilibrium in $(\mathbf{u} + H) \cap \mathbb{R}^{\mathcal{S}}_{\geq 0}$ given by $\lim_{t \to \infty} \mathbf{x}(t) = \alpha$.

A key observation from Theorem 1 is that not all choices of information molecules will guarantee the stability of the external biochemical system. The conditions in Theorem 1 place constraints on the choice of information molecules. In particular, the conditions suggest that the information molecules should behave similarly to enzymes for chemicals in the biochemical system.

IV. Conclusions

We have introduced the notion of *cognitive molecular communications* and identified an analogy with cognitive radio in wireless communications. This reveals a number of design strategies to tackle the problem of coexistence in molecular communications and the important role of chemical reaction network theory. However, there remain several open questions. For instance, what insights can be obtained for more general reaction-diffusion networks? Another issue is how the molecular communication system can obtain information about the dynamics of the biochemical system. In particular, when is it possible for the molecular communication system to adapt to the presence of new biochemical systems?

References

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[2] M. Egan, T. Mai, T. Duong, and M. Di Renzo, “Coexistence in molecular communications,” *Accepted for publication in Nano Communication Networks*, 2018.

[3] A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, “Breaking spectrum gridlock with cognitive radios: an information theoretic perspective,” *Proceedings of the IEEE*, vol. 97, no. 5, pp. 894–914, 2009.

[4] M. Miller and B. Bassler, “Quorum sensing in bacteria,” *Annu. Rev. Microbio.*, vol. 55, pp. 165–199, 2001.

[5] K. Srinivas, A. Eckford, and R. Adve, “Molecular communication in fluid media: the additive inverse Gaussian noise channel,” *IEEE Transactions on Information Theory*, vol. 58, no. 7, pp. 4678–4692, 2012.

[6] M. Egan, T. Mai, T. Duong, and M. Di Renzo, “Coordination via advection dynamics in nanonetworks with molecular communication,” in *Proc. IEEE International Conference on Communications (ICC)*, 2018.

[7] M. Feinberg, “Chemical reaction network structure and the stability of complex isothermal reactors–i. the deficiency zero and deficiency one theorems,” *Chemical Engineering Science*, vol. 42, no. 10, pp. 2229–2268, 1987.