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Evolutionary Game Theory Perspective on Dynamic Spectrum Access Etiquette

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ABSTRACT In this paper, we describe the long-term evolution of societies of secondary users in dynamic spectrum access networks. Such an understanding is important to help us anticipate future trends in the organization of large-scale distributed networked deployments. Such deployments are expected to arise in support of a wide variety of applications, including vehicular networks and the Internet of Things. Two new biologically-inspired spectrum access strategies are presented here, and compared with a random access baseline strategy. The proposed strategies embody a range of plausible assumptions concerning the sensing capabilities and social characteristics of individual secondary users. Considering these strategies as the basis of a game against the field, we use replicator dynamics within an evolutionary game-theoretic analysis to derive insights into the physical conditions necessary for each of the strategies to be evolutionarily stable. Somewhat surprisingly, we find that the physical channel conditions almost always uniquely determine which one of the three (pure) strategies is selected, and that no mixed strategy ever survives. We show that social tendencies naturally become advantageous for secondary users as they find themselves situated in network environments with heterogeneous channel resources. Hardware test-bed experiments confirm the validity of the analytic conclusions. Taken together, these results predict the emergence of social behavior in the spectrum access etiquette of secondary users as cognitive radio technology continues to advance and improve. The experimental results show an increase in the throughput of up to 90%, when strategy evolution is continuously operational, compared with any static strategy. We present use cases to envision the potential application of the proposed evolutionary framework in real-world scenarios.

INDEX TERMS Dynamic spectrum access, cognitive radio, evolutionary game theory, bio-social networking.

I. INTRODUCTION

Dynamic Spectrum Access (DSA) is a new paradigm in wireless networking, wherein radio spectrum frequencies may be assigned dynamically to remediate spectrum scarcity. Opportunistic Spectrum Access is a prominent DSA model in which any secondary user (SU) is allowed to use radio spectrum already licensed to a primary userİ (PU), as long as the PU is not subjected to interference. Opportunistic spectrum access naturally gives rise to the concerns of spectrum sensing (see [1], [2] and others), since its implementation requires detecting the presence of primary users [3], or equivalently, their absence, i.e. spectrum holes.

Cognitive Radio (CR) is a framework of enabling technologies which facilitate the implementation of self-configured DSA networks [4], providing for spectrum sensing, management, mobility, and sharing. Here we anticipate that the sensing technologies originally developed to coordinate PU-SU interactions [5], might be adapted and re-appropriated within the CR paradigm, to enable more harmonious SU-SU co-existence, thus ensuring more effective resource sharing. Channel selection is an inherently complex task in multi-channel CR networks, since each SU can (potentially) take a wide range of variables into consideration in its channel selection strategy, including: instantaneous Channel State

[45] J. M. Smith, *Evolution and the Theory of Games*. Cambridge, U.K.: Cambridge Univ. Press, 1982. [Online]. Available: http://dx.doi.org/10.1017/CBO9780511806292
[46] J. Nash, "The bargaining problem," *Econometrica*, vol. 18, no. 2, pp. 155–162, 1950. [Online]. Available: http://EconPapers.repec.org/RePEc:ecm:emetrp:v:18:y:1950:i:2:p:155-162
[47] Y. Zhang and M. Guizani, *Game Theory for Wireless Communications and Networking*, 1st ed. Boca Raton, FL, USA: CRC Press, 2010.
[48] V. Křivan, "Evolutionary games and population dynamics," in *Proc. Seminar Differ. Equ.*, vol. 2. Kamenice nad Lipou, Czech Republic, 2009, pp. 223–233.
[49] C. P. Roca, J. A. Cuesta, and Á. Sánchez, "Evolutionary game theory: Temporal and spatial effects beyond replicator dynamics," *Phys. Life Rev.*, vol. 6, no. 4, pp. 208–249, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1571064509000256
[50] *ns-3 WifiPhy Class Reference*. Accessed on Dec. 16, 2016. [Online]. Available: https://www.nsnam.org/doxygen/classns3_1_1_wifi_phy.html#details
[51] *ns-3 Yans-WiFi-Helper Class Reference*. Accessed Dec. 16, 2016. [Online]. Available: https://www.nsnam.org/doxygen/yanswifihelper_8cc_source.html
[52] M. Vanhoef and F. Piessens, "Advanced Wi-Fi attacks using commodity hardware," in *Proc. 30th Annu. Comput. Secur. Appl. Conf. (ACSAC)*, Dec. 2014, pp. 256–265.

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