From Channel Selection to Strategy Selection: Enhancing VANETs Using Socially-Inspired Foraging and Deference Strategies

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***Abstract*—Dynamic spectrum access (DSA) has been hailed as a possible panacea for the "spectrum crunch," drawing significant attention from researchers and industry alike. Here, we describe a novel system architecture for vehicular ad-hoc networks (VANETs) that relies on the DSA framework. In our system, nodes continuously and independently choose one of three strategies for channel selection. Two of these strategies are biosocially inspired, based on resource sharing behaviors known to have been prevalent in human societies over the course of their natural evolution. We view the strategy selection problem as an evolutionary game, proving that the only evolutionarily stable strategy is one in which all nodes utilize the same strategy that depends on the social characteristics of the nodes and the current channel conditions. Within our system, a specialized road side unit (RSU) continuously computes the game-theoretically optimal evolutionarily stable strategy and broadcasts this recommendation to all VANET nodes. Through `ns-3` simulation experiments across a range of social characteristics and channel condition scenarios, we demonstrate that a significant and robust improvement in utility (from 3% to 136%) is achieved when a large fraction of VANET nodes adopt the RSU's recommendation. The approach represents a bold departure from previous research which sought to track and micromanage channel resources from a short-term perspective, to one that provides VANET nodes with long-term recommendations for channel access *strategy*, both optimized for throughput and robust against attempts at circumvention by deviant users.**

***Index Terms*—Bio-social networking, cognitive radio, dynamic spectrum access, evolutionary game theory, VANET.**

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I. Introduction

INTELLIGENT transportation systems promise to deliver new safety and efficiency applications including pedestrian and vehicular safety, reduced fuel consumption, and reduced pollution. The design focus of new systems typically prioritizes one of several broad areas: safety, efficiency, convenience, and infotainment applications [1].

Vehicular Ad-hoc Networks (VANETs) are a key technology enabling intelligent transportation systems (Vegni *et al.* provide a good recent survey [2]). In VANETs, vehicles communicate directly with each other and with road-side infrastructure. VANETs are critical communication environments due to the fast mobility of vehicles. The Dedicated Short Range Communications (DSRC) licensed spectrum helps address some of the communication needs of VANETS. Using DSRC spectrum resources in a manner that scales with VANET size, however, requires robust resource sharing protocols.

Dynamic Spectrum Access (DSA) is a new resource sharing paradigm in wireless networking, in which radio spectrum frequencies are assigned dynamically to users in order to combat spectrum scarcity. Cognitive Radio (CR) is a framework of enabling technologies which facilitate the implementation of self-configuring DSA networks [3] that allow spectrum sensing, management and sharing. The sensing technologies developed to coordinate PU-SU interactions [4] can be adapted within the CR paradigm to enable more harmonious SU-SU co-existence, and ensure more effective resource sharing.

Here we will develop a bio-socially inspired approach to DSA, with the objective of enhancing the throughput of infotainment applications in VANETs. The impact of this is ensured by the multi-channel structure of the DSRC in the IEEE Wireless Access to Vehicular Environment (WAVE) standard: by improving infotainment throughput, greater residual bandwidth becomes available for safety traffic. Generally speaking, bio-socially inspired algorithms leverage knowledge about social and biological communities to design resource management solutions in a variety of domains. Here we apply prior findings on observed behaviors and structures of resource sharing and co-use in human societies [5] to design a new and highly effective DSA scheme for VANETs. In keeping with the bio-social paradigm in what follows, we will use the phrase "consuming a resource" and "transmitting in a channel" interchangeably.

[37] H. Li and D. K. Irick, "Collaborative spectrum sensing in cognitive radio vehicular ad hoc networks: Belief propagation on highway," in *Proc. 71st IEEE Veh. Technol. Conf. (Spring)*, May 2010, pp. 1–5.
[38] B. Aygun, R. J. Gegear, E. F. Ryder, and A. M. Wyglinski, "Adaptive behavioral responses for dynamic spectrum access-based connected vehicle networks," *IEEE Comsoc Tech. Committee Cogn. Netw.*, vol. 1, no. 1, pp. 45–48, Dec. 2015.
[39] S. Chen, Z. Liu, and D. Shen, "Modeling social influence on activity-travel behaviors using artificial transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1576–1581, Jun. 2015.
[40] A. Emrich, A. Chapko, D. Werth, and P. Loos, "Adaptive, multi-criteria recommendations for location-based services," in *Proc. 46th Hawaii Int. Conf. Syst. Sci.*, Jan. 2013, pp. 1165–1173.
[41] S. Mirri, C. Prandi, P. Salomoni, and L. Monti, "Social location awareness: A prototype of altruistic IoT," in *Proc. 8th IFIP Int. Conf. New Technol., Mobility and Security)*, Nov. 2016, pp. 1–5.
[42] X. Zheng, Z. Cai, J. Yu, C. Wang, and Y. Li, "Follow but no track: Privacy preserved profile publishing in cyber-physical social systems," *IEEE Internet Things J.*, vol. 4, no. 6, pp. 1868–1878, Dec. 2017.
[43] W. Song, "A distributed storage model for selfish and rational nodes," in *Proc. 6th Int. Conf. Biomed. Eng. Informat.*, Dec. 2013, pp. 717–722.
[44] A. Wisniewska, B. Khan, A. Al-Fuqaha, K. Dombrowski, and M. A. Shattal, "When brands fight over bands: Sociality in the cognitive radio ecosystem," in *Proc. IEEE Int. Conf. Commun.*, May 2017, pp. 1–6.
[45] A. Wisniewska, B. Khan, A. Al-Fuqaha, K. Dombrowski, and M. A. Shattal, "Social deference and hunger as mechanisms for starvation avoidance in cognitive radio societies," in *Proc. Int. Wireless Commun. Mobile Comput. Conf.*, Hoboken, NJ, USA, Mar. 2017, pp. 1063–1068.
[46] A. Wisniewska, M. A. Shattal, B. Khan, A. Al-Fuqaha, and K. Dombrowski, "From blindness to foraging to sensing to sociality: An evolutionary perspective on cognitive radio networks," *Mobile Netw. Appl.*, Oct. 2017. [Online]. Available: https://doi.org/10.1007/s11036-017-0950-6
[47] M. A. Shattal, A. Al-Fuqaha, B. Khan, K. Dombrowski, and A. Wisniewska, "Evolution of bio-socially inspired strategies in support of dynamic spectrum access," in *Proc. IEEE Int. Conf. Commun. Workshops*, May 2017, pp. 289–295.
[48] M. A. Shattal, A. Wisniewska, A. Al-Fuqaha, B. Khan, and K. Dombrowski, "Evolutionary game theory perspective on dynamic spectrum access etiquette," *IEEE Access*, vol. 6, pp. 13 142–13 157, Aug. 2018.
[49] A. Wisniewska and B. Khan, "Contention-sensing and dynamic spectrum co-use in secondary user cognitive radio societies," in *Proc. Int. Wireless Commun. Mobile Comput. Conf.*, Aug. 2014, pp. 157–162.
[50] A. Wisniewska, B. Khan, A. Al-Fuqaha, K. Dombrowski, and M. A. Shattal, "Social deference and hunger as mechanisms for starvation avoidance in cognitive radio societies," in *Proc. Int. Wireless Commun. Mobile Comput. Conf.*, Sep. 2016, pp. 1063–1068.
[51] J. M. Smith, *Evolution and the Theory of Games*. Cambridge, U.K.: Cambridge Univ. Press, 1982.
[52] J. Nash, "The bargaining problem," *Econometrica*, vol. 18, no. 2, pp. 155–162, 1950.
[53] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Networking Services*, IEEE Std 1609.3-2016 (Revision of IEEE Std 1609.3-2010), pp. 1–160, Apr. 2016.
[54] C. Xin, M. Song, L. Ma, G. Hsieh, and C. C. Shen, "On random dynamic spectrum access for cognitive radio networks," in *IEEE Global Telecommun. Conf.*, Dec. 2010, pp. 1–5.
[55] X. Mao and H. Ji, "Biologically-inspired distributed spectrum access for cognitive radio network," in *6th Int. Conf. Wireless Commun. Netw. Mobile Comput.*, Sep. 2010, pp. 1–4.
[56] R. Yao, K. He, Y. Sun, and Y. Wang, "Learning engine for cognitive radio based on the immune principle," in *2014 NASA/ESA Conf. Adaptive Hardware Syst.*, Jul. 2014, pp. 210–217.
[57] *Network Simulator ns-3*. 2018. [Online]. Available: https://www.nsnam.org
[58] *ns-3 WiFi Design*. 2018. [Online]. Available: https://www.nsnam.org/docs/models/html/wifi-design.html
[59] G. Pei and T. R. Henderson, "Validation of OFDM error rate model in ns-3," 2010. [Online]. Available: https://www.nsnam.org/ pei/80211ofdm.pdf
[60] ns-3 yans-wifi-helper class reference. 2016. [Online]. Available: https://www.nsnam.org/doxygen/yanswifihelper_8cc_source.html
[61] ns-3 wifiphy class reference. 2016. [Online]. Available: https://www.nsnam.org/doxygen/classns3_1_1_wifi_phy.html#details
[62] V. Krivan, "Evolutionary games and population dynamics," *Proc. Semin. Differential Equations: Kamenice nad Lipou*, vol. 2, pp. 223–233, 2009.

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