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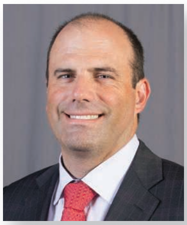

Communications and Sensing: An Opportunity for Automotive Systems

Like many of you, I am still working remotely, due to COVID-19, while writing this editorial. As in the past two years, I was planning to give an update on the magazine from our editorial board meeting. However, since ICASSP was remote, we have not yet scheduled the board meeting. Instead, I have decided to talk about a topic of personal interest: connections between communications and sensing in the context of vehicular systems. I believe that this is an important signal processing topic that brings together researchers from different technical committees and societies. This editorial is also relevant given the special issue articles and feature article found in this issue.

In past *IEEE Signal Processing Magazine* (*SPM*) editorials, I have discussed vehicular applications of signal processing, going toward 6G cellular communications, and new opportunities in communications as realized during a pandemic. In each of these articles I hinted at potential opportunities related to communications and sensing (especially radar). These topics have been featured in other *SPM* content including a two-part series on advances in radar systems for modern civilian and commercial applications (issues 4 and 5 in 2019) and a two-part series on autonomous vehicles (this issue and the upcoming January 2021 issue). There is also alignment with the IEEE Signal Processing Society (SPS) Autonomous Systems Initiative. In this editorial, I expand on the potential of combining communications and sensing in different ways.

Vehicles are being equipped with more sensors to support higher levels of automation. These sensors form a network on the vehicle, whose information is fused for tasks like trajectory planning and obstacle avoidance. Perhaps even more interesting, though, is the combination of sensing and communications that turns a network of vehicles into a cooperative perception system. The sensor data from each vehicle can be exchanged and fused to create a more accurate picture of the environment, leveraging the multimodality of the sensors and their different perspectives. Imagine the contrast with sensor networking research from two decades ago [1], which envisioned networks of low-power, low-cost sensors with limited communication capability. The networks of sensor networks in a transportation system has vastly more capable sensors, highly advanced signal processing, significant computational resources, automation, and much more communication capability.

For some of you, if you have read this far, you may be wondering why I have written another editorial that discusses communications. Where is the speech signal processing? Where is the biological signal processing? What about fast implementation of algorithms? In short, despite what I usually claim to my family, I do not know everything. On the aforementioned topics, I am working with *SPM*'s area editors to encourage more content in those areas as well. Apologies for—yet again—not straying from my core research area. This is an interesting time where communications and sensing are being combined in new ways in automotive, aerial, and other applications for consumers.

Using communication signals for radar

Radar and wireless communications share the same electromagnetic spectrum and have some common features in their waveforms. The purpose though is drastically different. In radar, the information (e.g., about a target) is captured in the system that transforms the transmitted signal to the observed received signal. For example, an observed Doppler shift may be related to a target's velocity. In wireless communication, the information (e.g., what is known at the transmitter but unknown to the receiver) is encoded into the transmit waveform, which is disrupted by a system (propagation channel, circuit impairments, noise) and observed at a receiver. The receiver removes the effects of the system (which normally involves tasks like channel estimation and equalization) with the objective of discovering what was transmitted. While both radar and communications may estimate aspects of the propagation environment, they each use them for a different purpose. Further, a communication waveform does not make the best radar waveform and vice versa.

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It is natural to consider ways that one type of signal can be used for the other type's purpose. Here I highlight some examples where a communication signal is used for radar. In essence, the objective is to exploit the known parts of the communication signal to estimate the unknown parameters related to the environment. It is an old idea. Early examples of bistatic radar using television signals are reviewed in [3]. What makes the topic current, though, is the use of low-power (relative to TV) access points, base stations, and devices for this purpose.

There are a number of recent examples involving Wi-Fi signals, much of it backed up with experimental data. For example, in [4] a Wi-Fi signal is used to perform through-wall imaging, for example, to detect the presence of a person. In [5], a Wi-Fi signal was used for gesture recognition. In essence, the micro-Doppler characteristics were used to train a machine learning method to classify different hand movements into one of a set of gestures. An application of this technology is whole-house audio volume control. In our work [6], we considered the use of the Wi-Fi for vehicles, known as *dedicated short-range communication*, for radar. The performance was not as good as what can be achieved by millimeter-wave automotive radar, but the cost is potentially much lower. In our other work in [7], we considered the use of the IEEE 802.11ad millimeter-wave communication signals for both communication (between two vehicles) and radar. The system gives high data rates and good radar performance, which gives extra robustness and provides additional security through diverse sources of information (the receiving vehicle broadcasting back its position, and the transmitting vehicle measuring the position of the receiving vehicle with radar).

Combining communications and radar together

In the aforementioned examples, a radar was designed to work with a given communication waveform. While it might share the same hardware as communication, no attempt was made to modify the communication waveform to better suit radar. It is possible to imagine, though, a system where tradeoffs are made, for example, that reduce communication throughput but increase radar system performance. Such tradeoffs have been a topic of recent work [8]. It is also the topic of a recent *SPM* article [9] as well as the article "Joint Radar-Communications Strategies for Autonomous Vehicles" by Ma et al. in this issue.

There are different ways that tradeoffs could be accommodated in a system. One approach would be to time multiplex between a communication waveform and a radar waveform. The time duration could be varied depending on the desired operational performance targets. The advantage of this approach is hardware reuse and potential ease of dealing with the full duplex problem (since radar waveforms are usually designed with that in mind). Another approach is a bit more integrated into the communication. The frequency of training symbols or pilots could be varied, for example to improve velocity estimation. The quality of the radar parameter estimates could improve and the channel estimate would be better for communications, but the data rate would decrease due to fewer data symbols. Systems in the future could be designed with both communication and radar sensing combined together in different combinations of joint, active, and passive radar to create for example a perceptive cellular network [10].

Leveraging sensors to aid communications

There has been a lot of work on using communication waveforms for radar. But can radar, or other sensors found in automated vehicles like cameras or lidar, be leveraged to support communications? This is interesting because such sensors use different spectrum than communications, and thus their use does not consume the limited and valuable communication resources. Further, they are already present on automated vehicles to support other automation tasks so their use does not necessarily have a cost or power penalty. The key question then is whether a millimeter-wave radar, a visible light lidar, or a visible light camera can infer something about the environment of relevance to the radio frequencies used by wireless communications?

A millimeter-wave radar has the potential to provide relevant information about a millimeter-wave communication link given the proximity of the frequencies. One early approach along these lines was presented in [11], where the radar was used to make an inference about good (or bad) communication directions to aid in millimeter-wave beam training. Intuitively, a radar should be able to help in other ways as well. For example, in a cellular communication scenario, a radar could track a vehicle that is communicating with the base station, reducing the overheads due to channel tracking. This makes sense because a radar at the base station can provide situational awareness that can be broadcast to surrounding vehicles to improve vehicle automation [12].

In contrast to bistatic radar with television transmissions, radar could also be used as a signal of opportunity. For example, work in [13] shows how millimeter-wave radar emissions from vehicles can be collected at the cellular base station and used for millimeter-wave beam training, which is a completely passive approach.

Deep learning is a valuable tool for uncovering the correlations between the sensed environment and the communication actions. Besides radar, automated vehicles have other sensors like lidar. Despite the drastic frequency differences, lidar data though can be used by a deep learning engine to detect if a link is in the line-of-sight state and also to reduce beam training overheads [14]. One could imagine that object detection and tracking via cameras (another topic with a significant deep learning component) could also be used in the same way.

Wrapping up

I believe that the interplay between sensing and communications has many opportunities for signal processing researchers. Fundamentals play a role in developing intuition and building algorithms to make good tradeoffs. Experimental work takes the spotlight given

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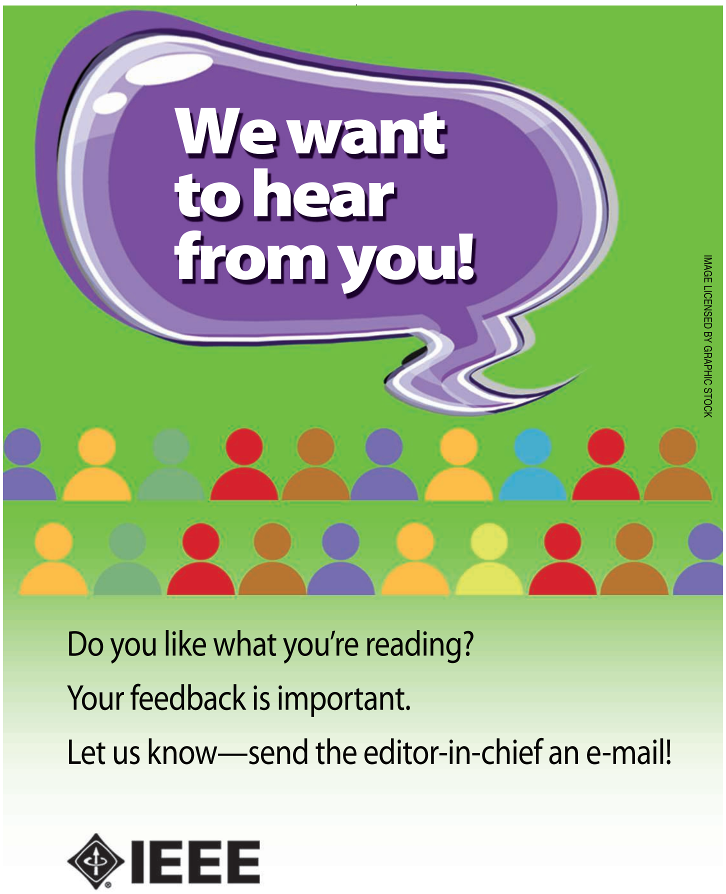

FROM THE EDITOR *(continued from page 4)*

the lack of models that connect different communication and sensing mechanisms. Many kinds of sensors may play a role beyond just radar, cameras, or lidar. Biosensors could be used to adapt communication in a wearable communication network. I hope to see many contributions to *SPM* in the future.

References

[1] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next century challenges: Scalable coordination in sensor networks," in *Proc. ACM Int. Conf. Mobile Computing and Networking*, Aug. 1999, pp. 263–270.

[2] IEEE Signal Processing Society autonomous systems initiative. [Online]. Available: https://ieeeasi.signalprocessingsociety.org

[3] H. D. Griffiths and N. R. W. Long, "Television-based bistatic radar," *Proc. Inst. Elect. Eng.*, vol. 133, Part F, pp. 649–657, Dec. 1986. doi: 10.1049/ip-f-1.1986.0104.

[4] F. Adib and D. Katabi, "See through walls with WiFi," in *Proc. ACM SIGCOMM Conf.*, 2013, pp. 75–86.

[5] Q. Pu, S. Gupta, S. Gollakota, and S. Patel, "Whole-home gesture recognition using wireless signals," in *Proc. 19th Annu. Int. Conf. Mobile Computing and Networking (MobiCom)*, 2013, pp. 27–38. doi: 10.1145/2500423.2500436.

[6] R. C. Daniels, E. R. Yeh, and R. W. Heath, "Forward collision vehicular radar with IEEE 802.11: Feasibility demonstration through measurements," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1404–1416, Feb. 2018. doi: 10.1109/TVT.2017.2758581.

[7] P. Kumari, J. Choi, N. González-Prelcic, and R. W. Heath, "IEEE 802.11ad-based radar: An approach to joint vehicular communication-radar system," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3012–3027, Apr. 2018. doi: 10.1109/TVT.2017.2774762.

[8] A. R. Chiriyath, B. Paul, and D. W. Bliss, "Radar-communications convergence: Coexistence, cooperation, and co-design," *IEEE Trans. Cogn. Commun. Netw.*, vol. 3, no. 1, pp. 1–12, Mar. 2017. doi: 10.1109/TCCN.2017.2666266.

[9] K. V. Mishra, M. R. Bhavani Shankar, V. Koivunen, B. Ottersten, and S. A. Vorobyov, "Toward millimeter-wave joint radar communications: A signal processing perspective," *IEEE Signal Process. Mag.*, vol. 36, no. 5, pp. 100–114, Sept. 2019. doi: 10.1109/MSP.2019.2913173.

[10] J. A. Zhang, A. Cantoni, X. Huang, Y. J. Guo and R. W. Heath, "Framework for an innovative perceptive mobile network using joint communication and sensing," in *Proc. IEEE 85th Vehicular Technology Conf. (VTC Spring)*, Sydney, Australia, 2017, pp. 1–5.

[11] N. Gonzalez Prelcic, R. Mendez-Rial, and R. W. Heath Jr., "Radar aided beam alignment in mm-wave V2I communications supporting antenna diversity," in *Proc. Information Theory and Applications*, San Diego, CA, Jan. 31–Feb. 5, 2016, pp. 1–7.

[12] A. Ali, N. González-Prelcic, R. W. Heath Jr., and A. Ghosh, "Leveraging sensing at the infrastructure for mmWave communication," *IEEE Commun. Mag.*, to be published.

[13] A. Ali, N. Gonzalez-Prelcic and A. Ghosh, "Automotive radar radiations as signals of opportunity for millimeter wave V2I links," in *Proc. 2019 53rd Asilomar Conf. Signals, Systems, and Computers*, Pacific Grove, CA, pp. 554–558. doi: 10.1109/IEEECONF44664.2019.9048967.

[14] A. Klautau, N. González-Prelcic, and R. W. Heath, "LIDAR data for deep learning-based mmWave beam-selection," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 909–912, June 2019. doi: 10.1109/LWC.2019.2899571.

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