A Smartphone-Based Healthcare Monitoring System—PHY Challenges and Behavioral Aspects

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Abstract. Within the broad theme of wireless healthcare systems, this paper focuses on emergency interventions. Specifically, we address one of the aspects of this problem, namely sensing and transmitting to a health center data regarding an emergency status. No dedicated infrastructure is assumed—rather, the premise is that existing wireless networks be utilized. Our goal is to enable quick and reliable access whenever an emergency arises. For system design, we describe an integrated solution based on the use of wireless/mobile technologies and of smartphones integrated by ad hoc sensors. We examine the possible use of licensed or unlicensed spectrum through two separate techniques: Interweaved Cognitive Radio and a novel version of Interference Alignment, that we call Interference Priority and is tailored to the specific problem of this paper. Validation based on the behavioral aspects of the system is also discussed.

Keywords: Wireless healthcare, Smartphone, Emergency communication, Cognitive radio, Interference alignment, Multi-agent reactive decisional systems.

1 Introduction

Following [1], we can categorize healthcare applications according to the following rubrics: (i) Prevention, (ii) Healthcare maintenance and checkup, (iii) Short-term (or home healthcare) monitoring, (iv) Long-term (or nursing home) monitoring, (v) Personalized healthcare monitoring, (vi) Incidence detection and management, and (vii) Emergency intervention. This paper focuses on the problems posed by last item, and aims at suggesting an integrated solution based on the use of wireless/mobile technologies and of smartphones integrated by *ad hoc* sensors. Our goal is to provide a design rationale and analysis tools for a

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healthcare system whereby a patient's vital parameters can be constantly sensed and updated round-the-clock via a wearable wireless device, compared with patient data stored in a sensor memory, and transmitted to a center (along with supplementary data as needed) when an emergency status is detected. Aspects of this problem are:

① Choice of vital parameters to be monitored (heart beat rate, position of the patient to detect a fall, . . .), and sensors to be used.
② Need for quick detection of the emergency status. This could be done using results from "quickest detection" theory [2].
③ Transmission to the health center of data regarding the emergency status. Transmission should be fast and reliable, and adapted to the level of emergency.
④ Secrecy/security of information should be guaranteed.

The system we advocate operates as follows: The patient's vital parameters are periodically or constantly sensed and compared with stored data. If an anomaly is detected, a preliminary decision is made about its degree of urgency. Then, the data to be transmitted to the health center are selected, along with their transmission protocol, according to the urgency degree detected—the minimum amount of data to be transmitted is an alarm message, supplemented by the last reading of the vital parameters, and might require two-way communication.

This paper focuses on two design and analysis aspects: PHY-level challenges dictated by the system (Section 2), and its behavioral aspects (Section 3).

1.1 Sensing Vital Parameters

Health-care monitoring systems that are compact, lightweight, low-cost, have low power consumption, and are able to identify physiological signals reliably and stably, have long been advocated (see, e.g., [3] and references therein, and [4] for a recent advanced application). Continuous remote monitoring can be achieved by external or implanted sensors, which communicate with the external world in two steps. The first one uses a very-short-range communication technology (e.g., ZigBee- or Bluetooth-based—see also [5]) to connect with a smartphone, and the second transmits sensed data to a remote health data center using standard wireless infrastructure. Within such scheme, pure relay-based functionality of the smartphone may be inappropriate, as it may cause a large energy consumption. For this reason, context-aware processing and data filtering have been advocated to use sensors episodically rather than continuously, and hence reduce the amount of transmitted data [6].

1.2 Prioritization Aspects

Taking into account that reliability is the key factor for any vital-parameter monitoring system suitable for emergency interventions, transmission should be prioritized according to the effects of its delivery failure [7]. Several reliability-based prioritization systems exist, classifying failure consequences from "very low" to "very high" (the effect of a delivery failure might cost the loss of human life). Here, alarm signals will be given the highest priority. Real-time monitoring traffic for patient conditions are the second highest priority, while other medical applications are given a lower priority. One may further categorize priorities as *relative* and *absolute* [7]. Under relative priority, transmission resources is allocated proportionally to priority, while, under absolute priority, high-priority transmissions are granted exclusive access to the channel regardless of the possible presence of low-priority traffic. We can observe that, under relative priority, quality-of-service (QoS) cannot be guaranteed to highest-priority messages if there is a heavy load of low-priority traffic, and hence absolute priority should be chosen whenever an emergency message must be transmitted.

1.3 QoS

The QoS level must be calibrated to the specific system within medical applications (see, e.g., [7]). For example, life-critical emergency information transmission requires a latency shorter than other types of traffic (transmission of abnormal—but not life-threatening—vital parameters, or normal vital parameters) can tolerate. Along with conventional QoS metrics such as delay, throughput, and error rate, unconventional metrics have also been advocated, like medical diagnosability of the data (see, for example, the *weighted diagnostic distortion* discussed in [7]).

2 PHY Challenges

Once no dedicated infrastructure is assumed, two options are available: unlicensed or licensed use of the spectrum. We examine separately the two options, namely:

① Unlicensed use of the spectrum may be realized by Cognitive Radio, operating according to the "interweaving" paradigm [8]. Through spectrum sensing, secondary users can detect an empty spectrum space in which transmission is achieved with a modicum of interference from adjacent spectrum users.

② For primary utilization of licensed spectrum, we advocate a technique we call *Interference Priority (IP)*. This borrows notions from the recent concept of Interference Alignment (IA) [9, 10]. Its guiding principle is to prioritize transmissions by enhancing the spectral efficiency of emergency transmissions while keeping to a minimum the penalty on nonemergency transmissions. IP results in: (i) Higher bit rates, (ii) Broader coverage for critical emergency transmissions, and/or (iii) Lower power consumption, which in turn maps to longer battery lives.

2.1 Cognitive Radio

The version of interweaved cognitive radio we are advocating is based on a *spectrum pooling* concept, whereby the secondary user isolates a portion of the radio spectrum that is not being utilized by the primary user [11, 12]. The spectrum owned by the primary user is divided into subchannels, each assumed to be active at any time with probability less than one. The secondary user, which has the ability of sensing all subchannels, forms a link by combining a number of subchannels depending on their quality and bandwidths, and on the QoS requirements. In principle, results from channel sounding may dictate the number of subchannels to be used by the secondary user, and the adaptive choice of transmission parameters (transmitted power, use of multiple antennas, modulation format, bit rate, coding scheme, etc.). However, for the system examined here we focus on a simpler solution, based on channel sensing, which classifies each subchannel that can be used for emergency communication as a *white space* when it is completely empty—except for noise and adjacent-channel interference—and hence can be used by the secondary user without restriction, or a *black space* when it is fully occupied by primary-communication signals, interfering signals, and noise, and hence cannot be used. When N_s primary-user subchannels are white, they are ordered according to a suitable simple metric (for example, the energy measured in each of them), and the N best are picked to form the secondary link.

2.2 Coding Aspects

We may categorize two types of effects reducing the transmission throughput:

① Presence of thermal noise, fading, and channel impairments.
② Nonzero probability of mistaking a black space for a white one.

Now, while standard error-control coding of the information data can reduce the first effect, nonstandard solutions should be envisaged to compensate for the other one. A simple model for the system examined here, which holds when the transmitted messages are protected by powerful error-control codes but not by an ARQ mechanism (which would require a feedback subchannel and hence introduce further delay), is based on the concept of "block-erasure channel" [13]. As observed in [14, 15], if the packet transmitted over a secondary-user subchannel is received erroneously (i.e., the internal checksum of the packet does not match), then it may not be passed to the higher layers in the protocol stack. Consequently, the application layer sees this as an *erasure*. A packet is received erroneously in a subchannel if the joint effects of noise, fading, and interference from the primary user cause a detection error. This error may or may not be detected, so that an erasure may or may not be declared. A common simplifying assumption is that an erasure occurs if and only if there is a collision, while the packet is so protected by its error-control code that it is received correctly whenever there is no collision (this assumption is valid for high-enough SNR and powerful codes). Thus, under this channel model, a packet is either received correctly, or is lost. The validity of this model leads to advocacy of *erasure-correcting codes*. A family of erasure-correcting codes allowing simpler decoding, and one often advocated for cognitive-radio applications, is that of

Digital Fountain (DF) codes. The use of DF codes involves a computational complexity much lower than for block codes. Concatenation of a powerful error-control code (used within each packet) with an erasure-correcting code (across packets) yields a possible solution, as advocated and analyzed in [16]. Another solution, which does not require N to be large, is based on the use of low-density parity-check codes designed for the block-fading channel, and hence suitable for channels affected by erasures and independent errors. [17]

2.3 Interference Priority

For primary utilization of licensed spectrum, what we advocate a technique we shall refer to as *Interference Priority (IP)*, which borrows notions from the recently proposed concept of Interference Alignment (IA) [9, 10] as well as from more established spatial processing schemes [18]. The guiding principle in IP is to prioritize emergency transmissions, if necessary at the expense of nonemergency transmissions.

In contrast with IA, which is a symmetric strategy in the sense that the interference is aligned at each of the participating receivers, *in IP the interference is aligned only at the receiver for which the emergency transmission is intended.* The constraints on the emergency transmitter are relaxed, allowing it to focus on maximizing the performance of its own link, while the other participating transmitters not only respect the constraint of aligning at the emergency receiver but further minimize the strength of their interference thereon. Altogether, the emergency transmission enjoys a hefty boost, while the other transmissions do not. This translates into broader coverage for those critical events and/or lower power consumption (which, in turn, maps to longer battery lives). Moreover, the asymmetric nature of IP reduces the need for channel-state information; only the channel realizations from each transmitter to the health-care center receiver need be tracked by the transmitters. In IA, alternatively, all channel realizations between each participating transmitter and receiver must be tracked.

3 Behavioral Aspects—An Analysis

Due to its complex nature, also due to its reactive aspects, our system may be hard to specify and validate. To this end, we propose a formal model for its specification and validation. Our approach is based on the concept of a Multi-Agent Reactive Decisional System [19, 20, 21, 22, 23]. Indeed, agents and sensors are elements with a similar nature [24]: they are independent, stand-alone, do not contain information about their whole environment, and finally the creation of a number of agents in necessary quantity is possible. Thus, a sensor can be formally specified and checked as a Decisional Reactive Agent (DRA), and the whole system as a Multi-Agent Reactive Decisional System (MARDS).

The objective here is to use the agent based techniques to formally model and verify WSN behavior and especially its temporal properties. Such modeling and checking should reduce the uncertainty in the system, and ensure the early correction in the development process (prior to the implementation), as well as a higher quality error-free product.

3.1 WSN Behavior Formal Specification and Healthcare System

Formal wireless sensor networks (WSN) behavior specification and verification are essential to critical systems as pervasive healthcare systems, and especially to the network subsystem composed of environmental sensors deployed around mobile or nomadic devices belonging to the patient. Such modeling and checking is particularly needed by the self-organization between these nodes, as it helps to provide rich contextual information about the people to be monitored, as well as about necessary alerting mechanisms [25]. It is also essential for end-user healthcare monitoring applications [25] that the system should prove to be doing the job it was designed to accomplish. Faulty system components and exceptions must not result in system misbehavior.

3.2 DRA Based Approach

Numerous results have shown that the agent paradigm proves useful in the development of complex WSN. The approach we advocate is based on the Decisional Reactive Agent (DRA) paradigm, which is among the most useful concepts used for reactive system modeling, especially in modeling and checking of mobile systems. In reaction to a detected external action, the DRA is able to adapt its behavior in an autonomous way and generate a set of adequate decisions that have to be undertaken within adequate deadlines. DRA-related concepts aim at modeling WSN behavior as a set of interacting reactive agents composing an event-driven real-time system and identifying temporal properties to check its logical correctness, i.e., the adequacy of it responses to dynamics. These concepts can especially improve the robustness of the whole system, in case of failure or malfunctioning of one or several sensors.

A major issue in future research concerns the extension of a DRA-based approach to the Autonomic System view of WSN behavior, integrating other self-management properties as the automatic configuration of components, the automatic monitoring and control of resources to ensure the optimal functioning with respect to the defined requirements.

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References

1. Varshney, U.: Pervasive healthcare and wireless health monitoring. Mobile Netw. Appl. 12, 113–127 (2007)
2. Poor, H.V., Hadjiliadis, O.: Quickest Detection. Cambridge University Press (2009)

3. Chen, C.-M.: Web-based remote human monitoring system with intelligent data analysis for home health care. Expert Systems with Applications 38, 2011–2019 (2011)
4. Kromhout, W.W.: Got flow cytometry? All you need is five bucks and a cell phone. UCLA News (July 26, 2011), `newsroom.ucla.edu/portal/ucla/ucla-engineers-create-cell-phone-210982.aspx`
5. Abouei, J., Brown, J.D., Plataniotis, K.N., Pasupathy, S.: Energy efficiency and reliability in wireless biomedical implant systems. IEEE Trans. Inf. Technol. Biomed. 15(3), 456–466 (2011)
6. Mohomed, I., Misra, A., Ebling, M., Jerome, W.: Context-aware and personalized event filtering for low-overhead continuous remote health monitoring. In: 9th IEEE Int. Symp. on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2008), Newport Beach, CA, June 23-26, pp. 1–8 (2008)
7. Lee, H., Park, K.-J., Ko, Y.-B., Choi, C.-H.: Wirless LAN with medical-grade QoS for e-healthcare. Journal of Communications and Networks 13(2), 149–159 (2011)
8. Biglieri, E., Goldsmith, A., Greenstein, L.J., Mandayam, N., Poor, H.V.: Principles of Cognitive Radio. Cambridge University Press, Cambridge (2011) (to be published)
9. Cadambe, V.R., Jafar, S.A.: Interference alignment and degrees of freedom of the K-user interference channel. IEEE Trans. Inform. Theory 54(8), 3425–3441 (2008)
10. Maddah-Ali, M., Mohatari, A., Khandani, A.: Communication over MIMO X channels: Interference alignment, decomposition, and performance analysis. IEEE Trans. Inform. Theory 54(8), 3457–3470 (2008)
11. Čabrić, D., Mishra, S.M., Willkomm, D., Broderson, R.W., Wolisz, A.: A cognitive radio approach for usage of virtual unlicensed spectrum. In: 14th IST Mobile Wireless Summit 2005, Dresden, Germany, June 19-22 (2005)
12. Weiss, T., Jondral, F.: Spectrum pooling: An innovative strategy for the enhancement of spectrum efficiency. IEEE Commun. Mag. 42, S8–S14 (2004)
13. Guillén i Fàbregas, A.: Coding in the block-erasure channel. IEEE Trans. Inform. Theory 52(11), 5116–5121 (2006)
14. Kushwaha, H., Xing, Y., Chandramouli, R., Heffes, H.: Reliable multimedia transmission over cognitive radio networks using fountain codes. IEEE Proc. 96(1), 155–165 (2008)
15. Kushwaha, H., Xing, Y., Chandramouli, R., Subbalakshmi, K.P.: Erasure tolerant coding for cognitive radios. In: Mahmoud, Q.H. (ed.) Cognitive Networks: Towards Self-Aware Networks, pp. 315–331. J. Wiley & Sons, Chichester (2007)
16. Berger, C.R., Zhou, S., Wen, Y., Willett, P., Pattipati, K.: Optimizing joint erasure- and error-correction coding for wireless packet transmission. IEEE Trans. Wireless Commun. 7(11), 4586–4595 (2008)
17. Boutros, J.J., Guillén i Fàbregas, A., Biglieri, E., Zémor, G.: Low-density parity-check codes for nonergodic block-fading channels. IEEE Trans. Inform. Theory 56(9), 4286–4300 (2010)
18. Rashidi-Farrokhi, F., Foschini, G.J., Lozano, A., Valenzuela, R.A.: Link-optimal space–time processing with multiple transmit and receive antennas. IEEE Commun. Letters 5(3), 85–87 (2001)
19. Aaroud, A., Labhalla, S.E., Bounabat, B.: A new formal approach for the specification and the verification of multi–agent reactive system operating modes. International Journal for Information Processing and Technology (March 2001)
20. Aaroud, A., Labhalla, S.E., Bounabat, B.: Modelling the handover function of Global System for Mobile Communication. International Journal of Modelling and Simulation 25(2) (2005)

21. Bounabat, B.: Méthode d'Analyse et de Conception des Systèmes Orientée Objet Décisionnel. Application aux langages synchrones et aux systèmes répartis. Doctoral Dissertation, Cadi Ayyad University, Faculty of Sciences, Marrakech, Morocco (2000)
22. Bounabat, B., Romadi, R., Labhalla, S.E.: User's behavioural requirements specification for a reactive agent. In: CESA 1998, Nabeul-Hammamet, Tunisia, April 1-4 (1998)
23. Furbach, U.: Formal specification methods for reactive systems. Journal of Systems and Software (21), 129–139 (1993)
24. Podkorytov, D., Rodionov, A., Sokolova, O., Yurgenson, A.: Using Agent-Oriented Simulation System AGNES for Evaluation of Sensor Networks. In: Vinel, A., Bellalta, B., Sacchi, C., Lyakhov, A., Telek, M., Oliver, M. (eds.) MACOM 2010. LNCS, vol. 6235, pp. 247–250. Springer, Heidelberg (2010)
25. Alemdar, H., Ersoy, C.: Wireless sensor networks for healthcare: A survey. Computer Networks 54(15), 2688–2710 (2010)