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Research Article

Internet of Vehicles for E-Health Applications in View of EMI on Medical Sensors

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Wireless technologies are pervasive to support ubiquitous healthcare applications. However, RF transmission in wireless technologies can lead to electromagnetic interference (EMI) on medical sensors under a healthcare scenario, and a high level of EMI may lead to a critical malfunction of medical sensors. In view of EMI to medical sensors, we propose a joint power and rate control algorithm under game theoretic framework to schedule data transmission at each of wireless sensors. The objective of such a game is to maximize the utility of each wireless user subject to the EMI constraints for medical sensors. We show that the proposed game has a unique Nash equilibrium and our joint power and rate control algorithm would converge to the Nash equilibrium. Numerical results illustrate that the proposed algorithm can achieve robust performance against the variations of mobile hospital environments.

1. Introduction

Recent developments in cellular networks (e.g., Universal Mobile Telecommunication System, UMTS Network) have enabled the innovative application of E-health anytime and anywhere. However, RF transmission can result in electromagnetic interference (EMI) to all of medical sensors, and a high level of interference can even cause malfunction of medical sensors and potentially injure patients [1, 2]. Thus, the control of interference (e.g., through a joint power and rate control) is a critical issue to E-health and should be addressed under the environment of mobile hospital, which is defined as Internet of vehicles for E-health applications in this paper. So throughout this paper, we alternatively use the terms of mobile hospital and Internet of vehicles for E-health applications.

Soomro and Cavalcanti in [3] address the possibilities of using wireless technologies in a medical environment. Zhou et al. in [4] present the scheduling of heterogeneous data over body sensor networks. Rodrigues et al. in [5] present the data visualization for body sensor networks. However, the potential EMI problem is not discussed in these works. Phunchongharn et al. in [1, 2] present the issue of EMI under the scenario of a wireless local area network (WLAN) for E-health applications within a hospital, but the technology of WLAN is not applicable to our scenario, in which a mobile hospital covers a large-scaled area (e.g., a city or a town). Thus, the model and the power control algorithms in [1, 2] cannot be directly used in a mobile hospital environment, in which our work is interested. Joint power and rate control algorithms for wireless networks are firstly addressed in [6]. However, these algorithms allocate power and rate according to the channel conditions of users and do not take the potential EMI impact into account. In such a scenario, a wireless user who stays close to a medical sensor could be allowed to transmit data at a high level of power if only the user's communication channel is in good condition. However, the RF transmission at a high level of power would influence the operation of medical sensors. Such an improper power allocation by these algorithms may lead to the malfunction of EMI-sensitive medical sensors, so the aforementioned algorithms cannot be employed under the scenario of mobile hospital. *The importance of scheduling wireless transmission under a mobile hospital scenario as well as the lack of efficient algorithms for transmission scheduling motivates us to investigate how wireless users can adjust their power and data rate to achieve certain goals, such as maximizing the level of their utility while ensuring the minimal amount of EMI on medical sensors over Internet of vehicles for E-health applications*.

In this paper, we address the problem of dynamically scheduling wireless transmission for wireless users' networks under a mobile hospital environment. The objectives of this paper are to (i) maximize certain goals (e.g., utility of a game) of each user and (ii) protect the medical sensors from harmful interference. In this paper, we propose a game of power and rate control in a mobile hospital environment and address a robust joint power and rate control algorithm, which is shown to converge to the Nash equilibrium of game. *To the best of our knowledge, this is the first work which presents the joint power and rate control algorithms under a wireless network for E-health applications.* The primary contributions of this paper are: (i) addressing the framework of data transmission over Internet of vehicles for E-health applications; (ii) establishing a game model of joint power and rate control to minimize the amount of EMI on medical sensors; (iii) proposing a joint power and rate control algorithm which can converge to the Nash equilibrium of the proposed game.

2. Related Work of EMI on Medical Sensors

The earliest research on EMI in hospital environments mainly focuses on the immunity of medical equipment to mobile phones. Tan and Hinberg in [7] firstly propose that some types of medical equipments, such as ventilators, infusion pumps, and ECG monitors, are quite sensitive to the EMI from cellular phones. Then, an EMI susceptibility test is carried out by the Medicines and Healthcare Products Regulatory Agency (MHRA) of UK [8]; this test includes testing the EMI of mobile phones and personal communication networks. The test results show that external pacemakers, anesthesia machines, respirators, and defibrillators are also susceptible to EMI. Trigano et al. in [9] and Calcagnini et al. in [10] study the EMI of GSM mobile phones on pacemakers and infusion pumps, respectively. Their results show that infusion pumps and pacemakers are inhibited due to the EMI of GSM mobile phones. With the implementation of 3G mobile phone systems in the United States, Japan, Hong Kong, and so forth, the research of EMI effects on medical equipments in the 3G band has appeared [11, 12]. In 2007, the International Electrotechnical Committee (IEC) publishes the EN60601-1-2 standard, and the immunity levels are recommended as 3 V/m and 10 V/m for life-supporting equipment (e.g., blood pressure monitors and infusion pumps) and non-life-supporting equipment (e.g., defibrillators), respectively. In view of the advances of electromagnetic compatibility (EMC) technologies, some hospitals in Singapore and the UK relax the EMI restriction recommended in the EN60601-1-2 standard, and mobile phones are allowed to be used in some areas of hospitals [13]. Tang et al. in [14] discuss the EMI test in view of the recently developed EMC of medical equipment, and the test takes into account the EMI of GSM900, PCS1800, and 3G mobile communication systems. The testing results show that ECG monitors, radiographic systems, audio evoked potential systems, and ultrasonic fetal heart detectors are sensitive to EMI [14]. Based on the previous literature, it can be concluded that the medical equipment sensitive to cellular phones includes fetal monitors, infusion pumps, syringe pumps, ECG monitors, external pacemakers, respirators, anesthesia machines, and defibrillators [15].

The other research topics focus on the EMI from devices within a wireless local area network (WLAN), which usually works at the frequency band around 2.4 GHz. This frequency band is different from the frequency band which mobile phones work at, and the amount of EMI on a medical equipment is related to frequency bands. Given these reasons, the research on EMI in the scenario of wireless healthcare monitoring starts. Krishnamoorthy et al. in [16] measure the EMI on medical equipment from patient and doctor devices, which work around the 2.4 GHZ frequency bands; the measurement is undertaken in two hospitals. The results show that the maximal EMI record is 0.552 V/m, which is within the acceptable EMI range recommended by the EN60601-1-2 standard. However, the measurement in [16] has not considered the QoS of data transmitted by patient devices and healthcare staff devices. The policy on mobile phone utilization, such as turning off mobile phone, cannot be applicable for patient devices and healthcare staff devices in a wireless healthcare monitoring system [17]. In wireless healthcare monitoring systems, healthcare staff and patients should employ wireless devices for data transmission and communication, and the restriction on transmit power may reduce the quality of service (QoS) of data transmission, which may increase the risk of medical data loss. Therefore, a contradiction between transmit power restriction and QoS requirements exists in wireless healthcare monitoring systems. In addition, when multiple patient devices and healthcare staff devices transmit data simultaneously, the aggregated signals at medical equipment would cause a higher level of EMI to medical equipment, including life-supporting equipment (e.g., blood pressure monitors and infusion pumps) and non-life-supporting equipment (e.g., defibrillators) [1]. Phunchongharn et al. in [1] discuss the EMI in hospital environments, in view of the QoS of patient devices and healthcare staff devices. The conclusion is that EMI on most medical equipment is within the unacceptable range if the transmit power of a WLAN device is larger than 10 mW.

All the abovementioned researches do not consider the vehicular scenarios for healthcare applications, which are interesting to this paper, and thus the medical sensors in the test may not be vehicle-mounted and wearable medical sensors. In Section 3.1, we address a detailed experiment which includes the test of EMI impact on types of vehicle-mounted and wearable medical sensors.

3. Game Model

A typical mobile hospital environment is composed of vehicles for E-health applications, and these vehicles are mounted with a few medical sensors which can help doctors to monitor the condition of patients (see Figure 2). On the vehicle for E-health applications, doctors, healthcare staff, and the relatives of patients may use mobile phones due to these two issues: (1) doctors and nurses must report the conditions of patients over phone to the staff in a hospital or in a medical center to arrange the medical actions which will be taken at the arrival of patients. (2) Patients or their relatives need to contact their family members over mobile phone about the change of clinical situations as well as important information. However, the use of mobile phones may lead to EMI impact on nearby medical sensors [18]. EMI refers to the disturbance of electrical circuits due to electromagnetic induction or electromagnetic radiation which are emitted from an external source [19]. The disturbance may cause the degradation of circuit's performance, and the degradation can lead to a total loss of data.

In the following, we first present the implementation of medical data collection and transmission. Then, we address an experiment to show the effects of EMI on medical sensors. Also we address the model of EMI impact in this paper as a constraint of outrage-optimization problem, which is detailed in Section 3.1.

3.1. Implementation of Data Collection and Transmission. The transmission of data is composed of two layers: one layer is from sensors to a mobile phone via personal area networks (with the technologies of Bluetooth or Zigbee) within a vehicle, and the other layer is from a mobile phone on a vehicle to the medical center via wide area network (WAN, e.g., 3G or 4G networks). The latter layer of data transmission can be implemented as regular communicators (e.g., MSN or Tencent QQ). So we focus on the implementation of the former layer: the data transmission from sensors to a mobile phone. Specifically, we implement the data collection and transmission by designing an integrated circuit (IC) which can be embedded into a regular mobile phone.

By and large, the IC (its architecture is shown in Figure 1) is composed of six components, namely, the microcontrol unit (MCU), the communication module, the display module, the data acquisition module, the network interface, and the power supply module. The data acquisition module is modified from an off-the-shelf compact module that runs data acquisition algorithms, and this module consists of a gas-pump unit and a gas pressure sensor. The cellular communication module takes charge of transmitting the acquired data to a remote data server via wireless networks. The core component of this module is a Subscriber Identity Model (SIM300C), which enables the data to access both GSM and GPRS communication networks. As the core of our patient device, MCU would store and run communication protocols and control signal processing programs. In the IC, the controller we used is MSP430 from Texas Instruments, which is widely used for ultra low power applications. In addition, a power supply module offers a stable power supply to the patient device. The display module controls the screen that shows all the information to the user. The interface is responsible for interaction between a mobile phone and the other phones or computers. Specifically, an interface could be used either to transfer medical data from sensors to a mobile phone or to debug programs running on the mobile phone.

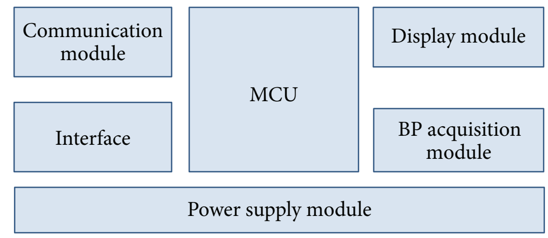

Figure 1: Architecture of an IC for data collection and transmission.

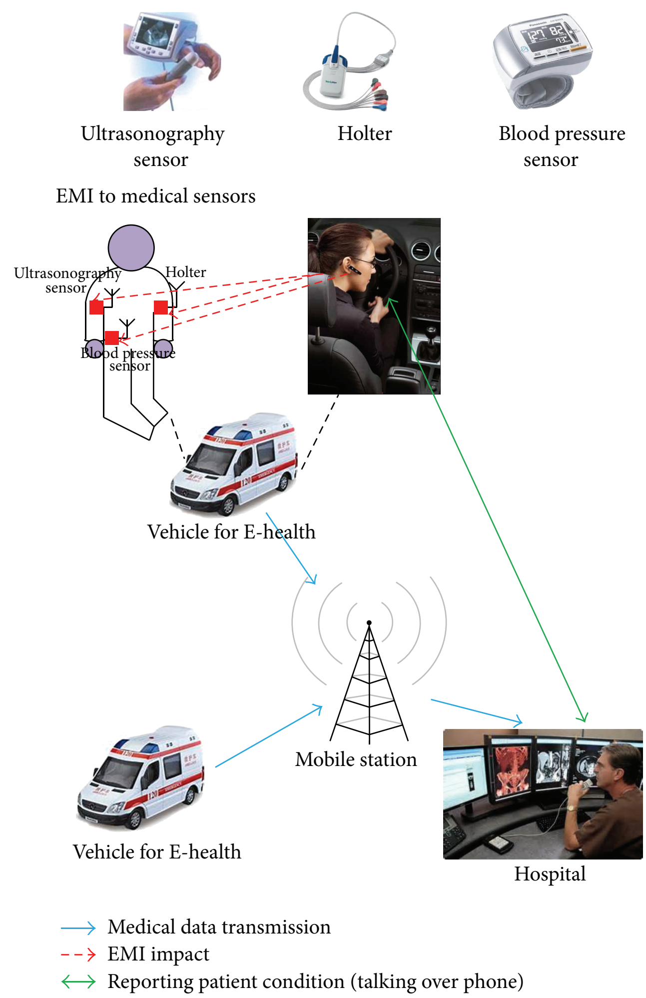

Figure 2: The figure illustrates the Internet of vehicles for E-health applications.

3.2. Experiment of Testing EMI Effects. In this experiment, we test the EMI impact on 50 types of vehicle-mounted and wearable medical sensors from the cellular phones operated by China Mobile, China Unicom, China Telecom. These cellular phones are with the technologies of GSM-900/1800, CDMA2000, and TD-LTE, and their average transmit power is 0.8 W.

The test is carried out in an anechoic chamber in order to exclude EMI impact from the other sources of RF emission, such as from telecommunication systems. The test procedures are detailed as follows: (a) tabletop sensors are placed on a table 80 cm above the floor, and floor-standing sensors are placed on the floor. Both the tabletop sensors and the floor sensors are vacillated to simulate the vacillation during the moving of a vehicle; (b) one investigator who operates a mobile phone controls the maximal power output (0.8 W), while another investigator monitors the working status of medical sensors; (c) the mobile phone is gradually brought closer to the medical sensor. If the degradation of performance of sensors occurs, the mobile phone is turned off to check if the performance degradation ceases, which shows whether the degradation is reversible or irreversible; (d) the EMI impact on medical sensors, reversible or irreversible, as well as the distance between medical sensors and mobile phones at the degradation of performance is recorded.

Test result shows that EMI from cellular phones causes the performance degradation of 68% of medical sensors within a 2 m distance away from the cellular phones. Typical degradation in the test includes (a) artifact in images of ultrasound sensors; (b) noise on biomedical signals, such as electrocardiograph (ECG) and electroencephalogram (EEG); (c) sensor malfunction in infusion pumps, syringe pumps, and ventilators; (d) change of operating mode of external pacemakers, such as from aynchronized to fixed rate. This result is in line with [1, 2].

Most of the problems of performance degradation are due to the component parasitics, and it represents the stray reactive elements which have been found in every component, whether a passive or active component. Capacitors have series inductance, which can lead to a series resonant circuit. Wound inductors have interwinding capacitance, which can lead to a parallel resonant circuit. These circuits resonate at the frequencies from 5 MHz to 1000 MHz. Besides the issue of component parasitics, the other issues which may lead to the performance degradation of medical sensors include ground impedance, poor cable shielding, and stray internal coupling paths. [20–23].

3.3. Mobile Hospital Environment. A typical mobile hospital environment consists of both life-supporting and non-life-supporting medical sensors, either wearable or vehicle-mounted sensors. The medical data which are collected by medical sensors are required to be sent to the doctors, who are staying in a hospital to make the plan of taking actions on the patient once the vehicle arrives at the hospital. Also the medical staff on the vehicle need to report the condition of patients over phone to doctors, and the use of mobile phone may lead to EMI on medical sensors nearby. The life-supporting medical sensors contain electronic components which are sensitive to EMI, so they are more sensitive to the impact of EMI than non-life-supporting sensors. Life-supporting medical sensors include wearable pacemakers, and non-life-supporting medical sensors include blood pressure sensors and Holter for ECG monitoring.

Both the abovementioned life-support sensors and non-life-support sensors may have different requirements on the transmit power of a wireless user to ensure that the user's RF transmission causes an acceptable level of EMI on medical sensors. The maximal potential transmit power of each wireless user should satisfy all of these requirements. To the best of our knowledge, Phunchongharn et al. in [1] firstly address how to model the EMI effects on medical sensors and calculate the maximal potential transmit power of a wireless user subject to the EMI constraints. Mathematically, the constraints on transmit power of a wireless user can be shown in (1), for life-support medical sensors and non-life-support medical sensors, respectively [1]:

$$\begin{aligned} &\sum_{i\in G}\frac{\mu_1\sqrt{P_i}}{D_i(p)} \le E_{\mathrm{NLS}}(p), \quad \text{for } p \in M_1 \\ &\sum_{i\in G}\frac{\mu_2\sqrt{P_i}}{D_i(q)} \le E_{\mathrm{LS}}(q), \quad \text{for } q \in M_2, \end{aligned} \tag{1}$$

where $E_{\mathrm{NLS}}(p)$ and $E_{\mathrm{LS}}(q)$ are the acceptable EMI levels for non-life-support sensor p and life-support sensor q, respectively; P_i is transmit power of wireless user i; $D_i(p)$ and $D_i(q)$ are the distances between the transmitter of user i and non-life-support sensor p or life-support sensor q; μ_1 and μ_2 are constant, and their values suggested by IEC 60601-1-2 are 7 and 23, respectively [1]. G represents the set of wireless users in the Internet of vehicles. M_1 represents the set of non-life-support sensors, while M_2 represents the set of life-support sensors.

Let

$$A = \begin{pmatrix} \dfrac{\mu_1}{D_1(1)} & \cdots & \dfrac{\mu_1}{D_n(1)} \\ \cdots & \cdots & \cdots \\ \dfrac{\mu_1}{D_1(m_1)} & \cdots & \dfrac{\mu_1}{D_n(m_1)} \\ \dfrac{\mu_2}{D_1(1)} & \cdots & \dfrac{\mu_2}{D_n(1)} \\ \cdots & \cdots & \cdots \\ \dfrac{\mu_2}{D_1(m_2)} & \cdots & \dfrac{\mu_2}{D_n(m_2)} \end{pmatrix}, \tag{2}$$

and $x_i = \sqrt{P_i}$; we can represent (1) as

$$AX \le B, \tag{3}$$

where m_1 is the cardinality of M_1, m_2 is the cardinality of M_2, $X = [x_1, \ldots, x_{m_1+m_2}]^T$, $B = [E_{\mathrm{NLS}}(1) \cdots E_{\mathrm{NLS}}(m_1), E_{\mathrm{LS}}(1) \cdots E_{\mathrm{LS}}(m_2)]^T$.

Remark 1. When the number of rows of A is equal to n, that is, $m_1 + m_2 = n$, then, we can obtain the unique solution $X = A^{-1}B$.

Remark 2. When the number of rows of A is less than n, that is, $m_1 + m_2 < n$, then, the linear equation is underdetermined. We select the optimal one from infinite solutions subject to the maximization of $\sum_{i\in G} P_i$.

Remark 3. When the number of rows of A is larger than n, that is, $m_1 + m_2 > n$, then, the linear equation is overdetermined. We relax the constraints of (1) with the best approximation, that is, $\min_X |AX - B|$. So $X = (A^T A)^{-1} A^T B$.

Remark 4. Given the set of wireless users G, the maximal transmit power of any wireless user i (denoted as $\overline{P}_i(G)$) can ensure that all of medical sensors are free from EMI effects when $m_1 + m_2 \le n$ (see Remarks 1 and 2) and also ensure that the total amount of EMI on medical sensors is minimized when $m_1 + m_2 > n$ (see Remark 3), since under the latter scenario, the power allocation can ensure $\min_X |AX - B|$.

Definition 5. The maximal potential transmit power of user i (i.e., $\overline{P}_i(G)$) to minimize the total amount of EMI on medical sensors, as obtained from Remark 4, is defined as the maximal effective transmit power (METP). The METP (i.e., $\overline{P}_i(G)$ for user i) will be employed to establish the game model in Section 3.2 (see Theorem 11) as well as to develop the joint power and rate control algorithm in Section 3.2 (see Remark 8).

3.4. The Game Model. In this section, considering a cellular network in which wireless users are randomly distributed in the coverage area, we address a noncooperative joint transmit power and rate control game. In this game, we employ a commonly used utility, which is proposed in [24] and can be characterized as a logarithmic function of power and rate with a squared pricing item. By and large, three common requirements in wireless communications motivate the proposal of utility in [24].

(i) Each wireless user aims to achieve higher level of signal to interference plus noise ratio (SINR), which is defined as

$$\mathrm{SINR}_i = \frac{P_i h_{ii}/R_i}{\sum_{j\neq i} P_j h_{ji} + N_i}, \tag{4}$$

where P_i and R_i denote the transmit power and data rate of user i, respectively; h_{ji} denotes the channel condition between users i and j; N_i denotes the additive white Gaussian noise.

(ii) Each wireless user aims to achieve a higher data rate.

(iii) When the interference level is high, each wireless user is inclined to increase its power level or decrease its data rate.

The proposed utility in [24] can exactly meet the three common requirements in the wireless communication networks. Mathematically, it can be presented as

$$\widehat{u}_i(P_i, R_i) = \log(\beta_1 P_i + \beta_2 R_i) - \frac{\lambda}{2}\left(\frac{\beta_1}{\beta_2} P_i^2 + \frac{\beta_2}{\beta_1} R_i^2\right), \tag{5}$$

where λ is the pricing factor; β_1 and β_2 are adjustable parameters.

The game with utility of (5) can be modeled as

$$\max_{0 \le P_i \le \overline{P}_i(G)} \widehat{u}_i(P_i, R_i) \quad i = 1, 2, \ldots, N, \tag{6}$$

where $\overline{P}_i(G)$ is METP, which is defined in Definition 5.

Theorem 6. *There exists a unique Nash equilibrium in the game of (6) when $\overline{P}_i(G) = \infty$, and at the Nash equilibrium (P_i^*, R_i^*), the following equations hold:*

$$P_i^* = \sqrt{\frac{1}{2}\frac{\beta_2}{\beta_1 \lambda}}, \qquad R_i^* = \sqrt{\frac{1}{2}\frac{\beta_1}{\beta_2 \lambda}}. \tag{7}$$

Proof. We show that the utility is a jointly concave function of P_i and R_i by calculating its second derivatives; that is,

$$\begin{aligned} \frac{\partial^2 \widehat{u}_i}{\partial P_i^2} &= -\frac{\beta_1^2}{(\beta_1 P_i + \beta_2 R_i)^2} - \lambda \frac{\beta_1}{\beta_2}, \\ \frac{\partial^2 \widehat{u}_i}{\partial R_i^2} &= -\frac{\beta_2^2}{(\beta_1 P_i + \beta_2 R_i)^2} - \lambda \frac{\beta_2}{\beta_1}, \\ \frac{\partial^2 \widehat{u}_i}{\partial R_i \partial P_i} &= -\frac{\beta_1 \beta_2}{(\beta_1 P_i + \beta_2 R_i)^2}. \end{aligned} \tag{8}$$

It is obvious that $\partial^2 \widehat{u}_i/\partial P_i^2 \le 0$, $\partial^2 \widehat{u}_i/\partial R_i^2 \le 0$, $(\partial^2 \widehat{u}_i/\partial P_i^2)(\partial^2 \widehat{u}_i/\partial R_i^2) - (\partial^2 \widehat{u}_i/\partial R_i \partial P_i)^2 \ge 0$ are strict inequalities. Thus, the utility is a strictly concave function on (P_i, R_i). Also the utility is continuous on (P_i, R_i). Since the strategy space of (P_i, R_i) is a compact, convex, and nonempty subset of two-dimensional Euclidean space of real numbers, from Theorem 1.2 in [25], the proof of a unique Nash equilibrium of (6) follows.

Recall the first derivative of u_i with respect to (P_i, R_i) and write

$$\begin{aligned} \frac{\partial \widehat{u}_i}{\partial P_i} = 0 &\longrightarrow \frac{\beta_2}{\beta_1 P_i + \beta_2 R_i} - \lambda P_i = 0, \\ \frac{\partial \widehat{u}_i}{\partial R_i} = 0 &\longrightarrow \frac{\beta_1}{\beta_1 P_i + \beta_2 R_i} - \lambda R_i = 0. \end{aligned} \tag{9}$$

We can conclude that the Nash equilibrium (P_i^*, R_i^*) satisfies (7). □

Remark 7. Theorem 6 indicates the iterative algorithm for updating (P_i, R_i) [24]:

$$\begin{aligned} \left(P_i^{n+1}, R_i^{n+1}\right) &= \left(\mathbf{I}^{\mathbf{P}}\left(P_i^n, R_i^n\right), \mathbf{I}^{\mathbf{R}}\left(P_i^n, R_i^n\right)\right), \\ \mathbf{I}^{\mathbf{P}}\left(P_i^n, R_i^n\right) &= \sqrt{\frac{1}{2}\frac{\beta_2}{\beta_1 \lambda}}, \\ \mathbf{I}^{\mathbf{R}}\left(P_i^n, R_i^n\right) &= \sqrt{\frac{1}{2}\frac{\beta_1}{\beta_2 \lambda}}, \end{aligned} \tag{10}$$

where n denotes the nth iteration.

The iterative power and rate updating algorithm proposed in [24] does not take into account the METP ($\overline{P}_i(G) = \infty$); thus the Nash equilibrium (P_i^*, R_i^*) could reach above METP, which would cause harmful EMI to medical sensors. In the following, we propose a novel iterative power and rate updating algorithm to ensure that the proposed algorithm converges to a fixed point below METP.

Remark 8. Theorem 6 indicates when $P_i < \overline{P}_i(G)$, that is, the transmit power of user i is lower than its METP, we have $R_i = \sqrt{(1/2)(\beta_1/\beta_2\lambda)}$ from (9); when $P_i = \overline{P}_i(G)$, that is, the transmit power of user i reaches its METP, we have $R_i = (-\beta_1\lambda\overline{P}_i(G) + \sqrt{(\beta_1\lambda\overline{P}_i(G))^2 + 4\beta_1\beta_2\lambda})/2\beta_2\lambda$ from (9).

3.5. Joint Power and Control Algorithm

Remark 9. In view of Remark 8, we propose the following iterative algorithm for updating (P_i, R_i):

$$\left(P_i^{n+1}, R_i^{n+1}\right) = \left(\mathbf{U}^{\mathbf{P}}\left(P_i^n, R_i^n\right), \mathbf{U}^{\mathbf{R}}\left(P_i^n, R_i^n\right)\right),$$

$$\mathbf{U}^{\mathbf{P}}\left(P_i^n, R_i^n\right) = \begin{cases} \sqrt{\dfrac{1}{2}\dfrac{\beta_2}{\beta_1\lambda}}, & \text{if } P_i^n \le \overline{P}_i(G), \\ \overline{P}_i(G), & \text{if } P_i^n > \overline{P}_i(G), \end{cases}$$

$$\mathbf{U}^{\mathbf{R}}\left(P_i^n, R_i^n\right) = \begin{cases} \sqrt{\dfrac{1}{2}\dfrac{\beta_1}{\beta_2\lambda}}, \\ \quad \text{if } P_i^n \le \overline{P}_i(G), \\ \dfrac{-\beta_1\lambda\overline{P}_i(G) + \sqrt{\left(\beta_1\lambda\overline{P}_i(G)\right)^2 + 4\beta_1\beta_2\lambda}}{2\beta_2\lambda}, \\ \quad \text{if } P_i^n > \overline{P}_i(G), \end{cases} \tag{11}$$

where n denotes the nth iteration; $\overline{P}_i(G)$ is defined as Definition 5.

Algorithm in Remark 9 indicates that we force the transmit power to be $\overline{P}_i(G)$ when P_i^n reaches above $\overline{P}_i(G)$ in order to ensure the minimal amount of EMI on medical sensors.

Lemma 10 (Brouwer's Fixed Point Theorem). *Let $S \subseteq R^n$ be compact and convex and $F : S \to S$ a continuous function. There exists a $s \in S$ such that $s = F(s)$.*

Proof. Refer to [26]. □

Theorem 11. *The function $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ has a fixed point; that is, there exists a power vector $\mathbf{P}^* = [P_1, P_2, \ldots, P_M]$ such that $\mathbf{P}^* = \mathbf{U}^{\mathbf{P}}(\mathbf{P}^*)$.*

Proof. Since the function $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ is a continuous function of P_i, by Brouwer's Fixed Point Theorem in Lemma 10, showing the existence of a fixed point is equal to showing the existence of a compact and convex set S, such that $\mathbf{U}^{\mathbf{P}} : S \to S$. In the following, we fabricate such a set.

When $P_i^n \le \overline{P}_i(G)$, $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n) = \sqrt{(1/2)(\beta_2/\beta_1\lambda)} = \sqrt{(1/2)(\sum_{j\neq i} P_j h_{ji} + N_i)/\alpha_1\lambda h_{ii}} \ge g_i = \sqrt{(1/2)(N_i/\alpha_1\lambda h_{ii})}$. Let $\underline{g} = \min_i g_i$, $l_j = \max_i(h_{ji}/2\alpha_i\lambda h_{ii})$, and $\bar{l} = \max(\max_i g_i, \max_i l_i)$. We have $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n) = \sqrt{(1/2)(\sum_{j\neq i} P_j h_{ji} + N_i)/\alpha_1\lambda h_{ii}} \le \overline{g} = \sqrt{M\bar{l}}$. Then, we fabricate the set $\widehat{S} = \{\underline{g} \le P_i \le \max\{\overline{g}, \overline{P}_i^G\}\}$ such that $\mathbf{U}^{\mathbf{P}} : \widehat{S} \to \widehat{S}$. The proof follows. □

Theorem 11 indicates that a fixed point of $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ always exists. In the following, we show that its fixed point is unique and converges to the Nash equilibrium of game (6).

Definition 12. A function $F(\mathbf{x})$ is defined as a standard function, if it satisfies the following three conditions for all $\mathbf{x} \ge \mathbf{0}$: (1) positivity: $F(\mathbf{x}) \ge 0$; (2) monotonicity: if $\mathbf{x}' \ge \mathbf{x}$, then $F(\mathbf{x}') \ge F(\mathbf{x})$; (3) scalability: for all $\delta > 1$, $\delta F(\mathbf{x}) > F(\delta\mathbf{x})$.

Lemma 13. *If a standard function has a fixed point, then the fixed point is unique. Also the standard function will globally converge to this unique fixed point.*

Proof. Refer to [26]. □

Theorem 14. *The joint power and rate control algorithm will always converge to the unique Nash equilibrium of (6).*

Proof. By [26], if a standard function has a fixed point, then the fixed point is unique. We can easily show that $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ is a standard function. By Theorem 11 and Lemma 13, the fixed point of $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ is unique.

By [26], a standard function globally converges to its unique fixed point. Thus, the standard function $\mathbf{U}^{\mathbf{P}}(P_i^n, R_i^n)$ will globally converge to its unique fixed point, which is also the Nash equilibrium of game by Remark 8. At the Nash equilibrium, the data rate and power need to meet the relationship of (9) (see Theorem 6), and the algorithm in (10) exactly guarantees this relationship between data rate and power. Thus, the joint power and rate control algorithm always converges to the unique Nash equilibrium of game. □

4. Simulation and Discussion

We gather the data on Internet of vehicles from [27], in which a connection of network represents a transmit-receive pair of wireless users. In the simulation, the vehicle network contains 50 nodes, and each node has a probability of 0.1 using the mobile phone. Please note that in cities, when an ambulance is close to densely populated areas, it is possible that 50 terminals have EMI impact on medical devices at the same time. The average distance between terminals is 8 meters. Each terminal is moving with an arbitrary direction at a speed of 10 m/s (36 km/h). We clarify the characteristics of channel models in Section 3.1. Also we normalize the level of EMI E_{LS} or E_{NLS} (see (1)) to unity and perform about 100000 Matlab-based experiments to present the results.

4.1. Characteristics of Channel Models. We select the commonly used set of empirical channel models, which is specified in ITU-R recommendation M.1225 [28], for simulation. ITU-R M.1225 model is applicable for the test scenarios in urban and suburban areas outside the high rise core where the buildings are of nearly uniform height [28]:

$$\begin{aligned} L = {} & 40\left(1 - 4 \times 10^{-3}\Delta h\right)\log R \\ & - 18\log\Delta h + 21\log f + 80, \end{aligned} \tag{12}$$

Table 1: Parameters of propagation models in ITU-R recommendation M.1225 [28].

Tap	Relative delay (ns)	Average power (dB)	Doppler spectrum
1	0	0.0	Rayleigh
2	310	−1.0	Rayleigh
3	710	−9.0	Rayleigh
4	1090	−10.0	Rayleigh
5	1730	−15.0	Rayleigh
6	2510	−20.0	Rayleigh

where R [km] represents the distance between base station and mobile station; f [MHz] represents the carrier frequency; h [m] represents the base station antenna height, which is measured from the average rooftop level.

Each terrestrial test environment can be modelled as a channel impulse response model based on a tapped-delay line. The model is characterized by the number of taps, the time delay relative to the first tap, the average power relative to the strongest tap, and the Doppler spectrum of each tap. A majority of time-delay spreads are relatively small, while a few "worst case" multipath characteristics cause much larger delay spreads. Table 1 identifies the propagation model for each of 6 vehicular test cases. In all of these test cases, we consider the strength and relative time delay of signal components as well as Doppler shift and assume that each of 6 vehicular test cases occurs with the same probability. Specifically, the primary parameters to characterize each of propagation models include

(i) time delay-spread, its structure, and its statistical variability (e.g., probability distribution of time delay spread);

(ii) multipath fading characteristics (e.g., Doppler spectrum, Rician versus Rayleigh) for the envelope of channels.

4.2. Proposed Algorithm across Networks. In this section, we compare the convergence rate of our algorithm (11) under the scenarios of different random networks. For simplicity, we set $\beta_1 = \beta_2 = 0.5$ and investigate the convergence rate for different networks.

It is observed from Figure 3 that the algorithm of (11) under the networks with highly concentrated transmit/receive nodes (e.g., Exponential network) quickly converges to the fixed point (with the Intel Core i7-2760QM processor, the running time of each iteration is around 0.00014 s, so the total time of running the algorithm with 6000 iterations is 0.84 s. Given that the ambulance is moving at a speed of 10 m/s, the algorithm is feasible when the channel conditions are assumed to be invariant within a distance of 8.4 m. In a fast-varying mobile environment, we can use a more powerful processor to run the algorithm to ensure its feasibility), while the algorithm under the networks without highly concentrated transmit/receive nodes (e.g., Erdös-Rényi network) converges to the fixed point at a low rate. Indeed, the algorithm under the exponential network reaches the fixed point after 7000 iterations, while its convergence appears after 12000 iterations under the Erdös-Rényi network.

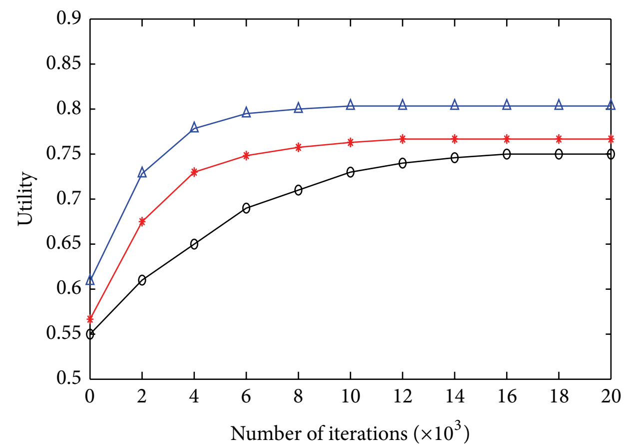

Figure 3: The figure illustrates the rate of convergence to the fixed point of our algorithm under different random networks. Blue line with "Δ" represents exponential network; red line with "∗" represents preferential attachment (scale-free) network; dark line with "o" represents Erdös-Rényi network.

Another result observed from Figure 3 is that higher utility can be achieved by exponential network, in which wireless users have only a single or few transmit/receive pairs, than by Erdös-Rényi network in which users have multiple transmit/receive pairs. This is because a user establishs transmit-receive pairs with most of the other users in Erdös-Rényi network, and thus one data transmission is easily influenced by the interference from the other transmissions. However, in the exponential network, the users establish transmit-receive pairs with only a single or few other users, and they suffer little interference from the other transmissions.

4.3. Impact of EMI. We first address the advantages of joint power and rate control to the increase of utility across wireless users. For the comparison of utility between using joint power and rate control as well as using power or rate control only, we employ the strategy of power control (proposed in [1] by setting R_i as a constant) as well as rate control (by setting P_i as a constant) as a benchmark. Figure 4 implies that the joint power and rate control can gain a higher average utility than only using the control of power or the control of rate, showing the benefits of using joint power and rate control to increase the utility. Also the value of average utility depends on the ratio of $\beta_1/(\beta_1 + \beta_2)$, and at the Nash equilibrium of the game, we have $R_i/(R_i + P_i) = \beta_1/(\beta_1 + \beta_2)$ (see Theorem 6). It is also observed from Figure 4 that the value of utility is symmetric with one peak at $\beta_1 = \beta_2$; this is because at the Nash equilibrium, the utility within the strategy space can be denoted as $\log(\sqrt{2\beta_1\beta_2/\lambda}) - \lambda^2/2$ (by substituting (12) into (6)), which is symmetric at the peak of $\beta_1 = \beta_2$ when $P_i \le \overline{P}_i(G)$.

In the following, we address the benefits of using the proposed algorithm to the decrease of EMI on medical sensors.

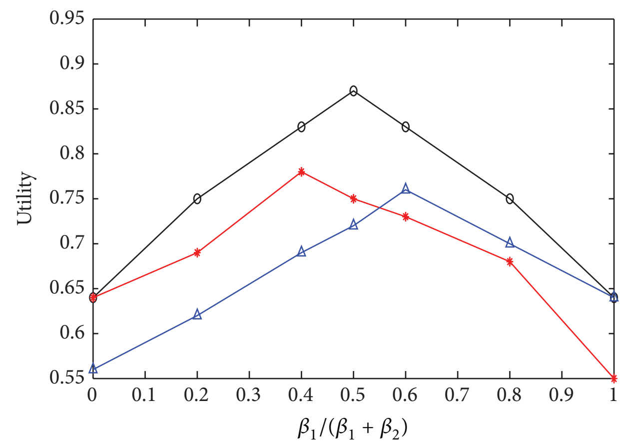

FIGURE 4: The figure shows the impact of power and rate control on the utility. Blue line with "Δ" denotes power control only; red line with "∗" denotes rate control only; dark line with "o" denotes joint power and rate control.

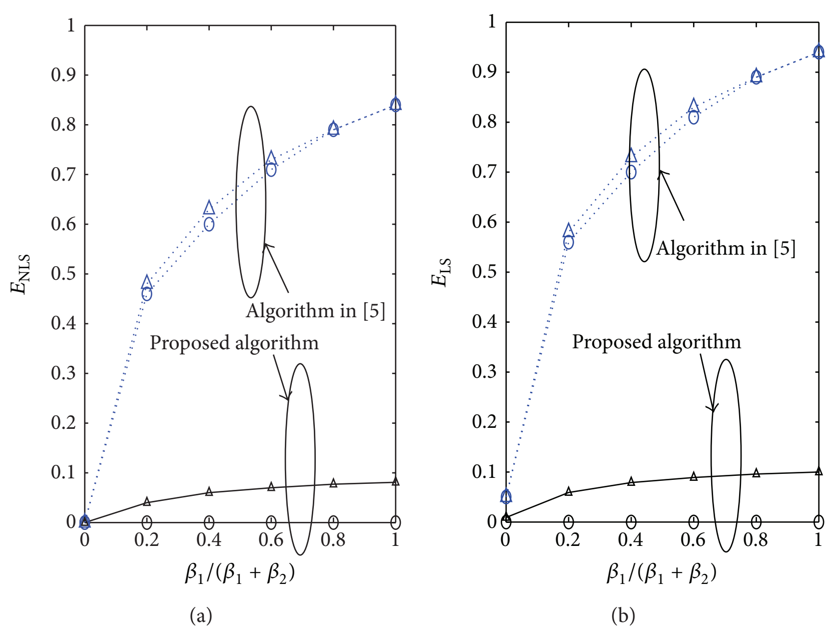

FIGURE 5: The figure shows EMI caused by RF transmission using our algorithm versus algorithm in [24]: the left shows the EMI on non-life-support sensors, while the right shows the EMI on life-support sensors. Blue and dashed line represents using algorithm in [24]; dark and solid line represents using our algorithm. Line with "Δ" represents the case of $m_1 + m_2 > n$; line with "o" represents the case of $m_1 + m_2 \leq n$.

Figure 5 shows the comparison of EMI on medical sensors caused by RF transmission between using our proposed algorithm (Remark 9) and using the algorithm proposed in [24] (Remark 7). Figure 5 implies that our proposed algorithm (EMI level below 0.1) can dramatically reduce the amount of EMI on medical sensors compared to the algorithm in [24] (EMI level up to 0.8). Also our algorithm can ensure that medical sensors are free from EMI when $m_1 + m_2 \leq n$ and can ensure the minimal amount of EMI when $m_1 + m_2 > n$. To put it another way, when we need to consider the EMI on a large number of medical sensors ($m_1+m_2 > n$), our algorithm can minimize the amount of EMI on medical sensors though it cannot keep medical sensors free from EMI as under the scenario of a small number of medical sensors ($m_1 + m_2 \leq n$).

5. Conclusions

We addressed a noncooperative game to maximize the utility of wireless users by controlling their transmit power and rate under a mobile hospital scenario. We proposed the joint power and rate control algorithm and showed that the algorithm would globally converge to a unique Nash equilibrium of game. Some of the key inferences drawn are as follows.

(i) Proposed joint power and rate control algorithm could dramatically improve the utility of wireless users and reduce the amount of EMI on medical sensors compared to current algorithm in [24], which is the most widely used power and rate control algorithm under nonmedical settings.

(ii) Under the networks with users who have highly concentrated transmit/receive pairs, the power and rate control algorithm can converge to the fixed point at a higher rate than under the networks in which transmit/receive pairs are evenly distributed among wireless users.

(iii) Networks with users who have highly concentrated transmit/receive pairs can achieve a higher utility than the networks in which transmit/receive pairs are evenly distributed among wireless users.

We are extending our results to the settings in which wireless users can be of different priorities. We would also like to extend our results to a dynamic setting; that is, the structure of Internet of vehicles is dynamically changing over time.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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