Bandwidth allocation in view of EMI on medical equipments in healthcare monitoring systems

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***Abstract*— To enhance the capacity of patients supported by in-hospital wireless monitoring systems, a bandwidth allocation scheme for the transmission of medical data in the WLAN is proposed. The problem of bandwidth allocation, subject to limited wireless bandwidth, quality of service (QoS) requirements of medical data transmission, and electromagnetic interference is modeled as an optimization problem. To solve this problem, we propose an algorithm based on genetic theory and analyze the computation time of this algorithm. Finally, based on this algorithm, we analyze the capacity of patients supported by the monitoring system.**

***Index Terms*— Wireless healthcare monitoring, dynamic programming, electromagnetic interference, genetic algorithm.**

I. INTRODUCTION

Recent developments in wireless local area (WLAN) networks have enabled the innovative application of wireless healthcare monitoring in hospitals. As the most recently published IEEE standard for WLAN, IEEE 802.11n employs the technologies of orthogonal frequency-division multiplexing(OFDM) and multiple-input multiple-output (MIMO) and can attain the data rate around 150Mbps [1]. Despite recent advances in WLAN, its wide application on in-hospital healthcare monitoring still faces several challenges. One of these challenges is the limited wireless resources, including the limited bandwidth and limited memory size of patient devices, to support the healthcare monitoring of numerous patients, especially in the case of developing countries with a large population. Another challenge is the different quality of service (QoS) requirements of medical data transmission due to different patient status. The medical data of a patient in emergent status must be transmitted to the monitoring center in a demanding delay requirement, and these data should be given the highest priority of transmission. Finally, the electromagnetic interference (EMI) on medical equipments would restrict the transmit power of patient devices or healthcare staff devices, which would reduce the network capacity in a wireless healthcare monitoring system.

To enhance the capacity of patients supported by the WLAN for healthcare monitoring, a novel bandwidth allocation scheme, subject to limited wireless resources, QoS requirements of medical data and EMI, is proposed in this paper. In this scheme, the problem to maximize the capacity of patients is modeled as a dynamic programming problem, and we propose an algorithm based on genetic theory to solve this problem. With the proposed algorithm for bandwidth allocation, we analyze the capacity of patients supported by the WLAN in healthcare monitoring systems.

II. RELATED WORK

In this section, we discuss the types of traffic in an in-hospital wireless monitoring system. Then, we introduce the constraints of transmit power of a patient device due to the EMI on medical equipments.

A. Traffic transmitted in the WLAN for healthcare monitoring

WLAN is responsible for the transmission of traffic between patient devices and the monitoring center. The traffic in the WLAN mainly include three categories: messages, video conferences and medical data with different QoS requirements. Therefore, the traditional scheme for bandwidth allocation is to allocate all the subcarriers of WLAN among three parts [2]: a message part, an application part and a data part. The message part is for the transmission of messages; the application part is for video conferences; the data part is for the transmission of medical data. However, the traditional scheme would lead to the underutilization of the application part, since video conferences do not occur all the time. The underutilization of bandwidth would further cause a smaller capacity of patients supported by the WLAN for in-hospital healthcare monitoring; the capacity of patients supported in a hospital is one of the most concerning problems in developing countries, in which the healthcare resources are usually insufficient for a large national population.

To enhance the capacity of patients supported by the WLAN in hospitals, we propose a novel scheme of data transmission in [3]. In this scheme, the application part is used to transmit medical data when not all the subcarriers allocated for video conference are busy. Therefore, we can store medical data in patient devices when all subcarriers are busy, while freeing the memory of devices by transmitting the stored medical data to the monitoring center when some subcarriers in the application part are idle. If the memory size of a patient device is unlimited and the required delay for data transmission is also unlimited, then, we do not necessarily employ extra subcarriers to transmit medical data. However, in reality, the memory size of a patient device is limited and the required delay is also limited. Therefore, some extra subcarriers specially for the transmission of medical data are required even with the proposed scheme for data transmission. The traditional scheme

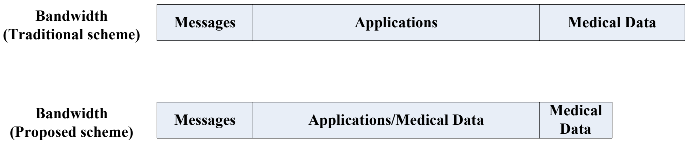

Fig. 1. Proposed scheme of bandwidth allocation [3].

and the proposed scheme for data transmission are shown in Fig.1. In comparison with the traditional scheme, the proposed scheme can enhance the capacity of patients [3]. Therefore, the following discussion is based on the proposed scheme for data transmission.

B. EMI to medical equipments

To our best knowledge, Phond et al. in [4] firstly propose the formula to calculate the maximal potential transmit power of a patient device subject to the EMI restriction. Medical equipments include life-support equipments and non-life-support equipments; different types of equipments may correspond to different requirements for the transmit power of a patient device and a healthcare staff device. The maximal potential transmit power should satisfy all these requirements. Mathematically, the constraints on transmit power can be shown in equation (1) and equation (2), for the cases of life-support medical equipments and non-life-support medical equipments, respectively.

$$\sum_{A=1}^{A_t} \frac{7\sqrt{P_{NLS}(A)}}{D_{NLS}(A)} + \sum_{x=1}^{X_t} \frac{7\sqrt{P_t(x)}}{D_x(p)} \leq E_{NLS}(p) \tag{1}$$

$$\sum_{A=1}^{A_t} \frac{23\sqrt{P_{LS}(A)}}{D_{LS}(A)} + \sum_{x=1}^{X_t} \frac{23\sqrt{P_t(x)}}{D_x(q)} \leq E_{LS}(q) \tag{2}$$

where $P_{NLS}(A)$ and $P_{LS}(A)$ are the maximal potential transmit power of a healthcare staff device A to satisfy the EMI requirement of a non-life-support equipment and a life-support equipment, respectively; $D_{NLS}(A)$ and $D_{LS}(A)$ are the distances from the healthcare staff device A to the non-life-support equipment and the life-supporting equipment, respectively; $E_{NLS}(p)$ and $E_{LS}(q)$ are the acceptable EMI levels for a non-life-support equipment p and a life-support equipment q, respectively; $P_t(x)$ is transmit power of a patient device x; $D_x(p)$ and $D_x(q)$ are the distances between the transmitter of the device x and the non-life-support p or the life-support equipment q; X_t and A_t are the number of patient devices and healthcare staff devices being working.

III. OPTIMAL BANDWIDTH ALLOCATION IN VIEW OF EMI

In a real hospital environment, patient devices, healthcare staff devices, life-support medical equipments and non-life-support medical equipments may operate at the same time. Therefore, the maximal potential transmit power of a healthcare staff device or a patient device should satisfy both equation (1) and equation (2) to avoid intolerable EMI on medical equipments. We denote the maximal transmit power at time slot k for patient device i as $P_{max}^{(k)}(i)$; then, the transmit power at time slot k for patient device i, $P^{(k)}(i)$ should be less than or equal to $P_{max}^{(k)}(i)$. In addition, medical data have different priorities according to patient status, and the medical data with a higher priority have a more demanding requirement of transmission delay. Usually, the patient status can be classified into 'high-degree (H)', 'low-degree (L)' and 'normal (N)', which represent the emergency degree of patient status.

Next, we discuss the method to maximize the capacity of patients supported by the WLAN given the total amount of bandwidth in this WLAN.

Let N_u be the number of patients, N_T be the total number of time slots during monitoring, $S^{(k)}$ be the number of special subcarriers in the kth $(k = 1, 2 \cdots N_T)$ time slot, $M_i^{(k)}[bits]$ be the amount of data in the memory of the ith patient device in the kth time slot, $B_i^{(k)}[Hz]$ be the bandwidth allocated to the ith device in the kth time slot, $\eta_i^{(k)}[bps/Hz]$ be the bandwidth efficiency of the ith device in the kth time slot, $a_i^{(k)}[bps]$ be the data arrival rate of the ith device in the kth time slot, $M_i^{\max}[bits]$ be the memory size of the ith device, $B_a^{(k)}[Hz]$ be the bandwidth for applications in the kth time slot, $T_c[s]$ be the duration of one time slot, $B_{total}[Hz]$ be the total amount of bandwidth; $\Delta B[Hz]$ be the bandwidth of one subcarrier, $\Delta T_1[s]$, $\Delta T_2[s]$ and $\Delta T_3[s]$ be the tolerable delay for data transmission as the patient status is 'H', 'L' and 'N', respectively. For simplicity, we assume $\Delta T_3 = \infty$, that is, the transmission of data corresponding to status 'N' has no delay requirement. Then, the problem of maximizing the patient capacity can be modeled as a dynamic programming problem, and this dynamic programming problem in the kth $(k = 1, 2 \cdots N_T)$ time slot can be denoted as

$$\begin{aligned}
&Max \quad N_u \\
&\quad s.t. \quad M_i^{(k)} = Max\left\{(a_i^{(k)} - \eta_i^{(k)} B_i^{(k)})T_c + M_i^{(k-1)}, 0\right\} \\
&\qquad\quad M_i^{(k)} \leq M_i^{\max} \\
&\qquad\quad \textstyle\sum_{i=1}^{N_u} B_i^{(k)} + B_a^{(k)} = S^{(k)}\Delta B + \sum_{i=1}^{N_u} B_i^{(k-1)} \\
&\qquad\quad \textstyle\sum_{i=1}^{N_u} B_i^{(k)} + B_a^{(k)} \leq B_{total} \\
&\qquad\quad a_i^{(k)} T_c \leq \eta_i^{(k)} B_i^{(k)} \Delta T_1 \;\; (i \in \mathbf{H}) \\
&\qquad\quad a_i^{(k)} T_c \leq \eta_i^{(k)} B_i^{(k)} \Delta T_2 \;\; (i \in \mathbf{L}) \\
&\qquad\quad P_i^{(k)} \leq P_{max}^{(k)}(i) \\
&\qquad\quad r_i^{(k)} = P_i^{(k)} \left|h_i^{(k)}\right|^2 \Big/ \left(B_i^{(k)} \sigma^2\right)
\end{aligned} \tag{3}$$

where $\eta_i^{(k)}$ is the bandwidth efficiency for patient device i at time slot k, and it is represented by equation (4) [1]; $P_i^{(k)}[W]$ is the transmit power of patient device i at time slot k; $\sigma^2[W/Hz]$ is the noise spectral density; $r_i^{(k)}$ is the signal to noise ratio (SNR) for patient device i at time slot k; $h_i^{(k)}$ is the channel fading for patient device i at time slot k; the channel fading in a hospital environment can be assumed as flat-fading [5], so for a particular patient device, the channel fading of each subcarrier can be represented by a common value. In addition, as shown in equation (4), the bandwidth efficiency of each subcarrier can also be represented by a common value.

$$\overline{\eta}_i(k) = \Big[\sum_{p=1}^{m} \exp\{p/r_i^k\} \sum_{l=n-m}^{(n+m-2p)p} a_{p,l} \\ \times \sum_{j=1}^{l+1} E_{l+2-j}\left(p/r_i^k\right)\Big]_i^{(k)} \quad (4)$$

In equation (3), the objective of this dynamic programming is to find the maximal N_u. The first constraint means that the amount of data in the memory equals that in the last time slot plus the data accumulated in this time slot. The second constraint means that the amount of data in the memory should be less than the memory size. The third constraint means that the total bandwidth consists of the bandwidth employed for applications (video conferences) and that employed for transmitting medical data. In addition, the total bandwidth in the kth time slot is equal to the total bandwidth in the $(k-1)$th time slot plus the bandwidth of special subcarriers in the kth time slot. The fourth constraint means that the total bandwidth utilized in the WLAN should be less than the given bandwidth of a WLAN. The fifth and the sixth constraints mean that the data in state 'H' and 'L' should satisfy delay requirements. The seventh and eighth constraints show the limit of transmit power and its corresponding signal-to-noise ratio.

We transform the problem of maximizing the capacity of patients, shown in equation (3), into the problem of minimizing the number of required subcarriers given the number of patients N_u. Then, we increase N_u, and the number of required subcarriers would also increase; the maximal number of patients supported by the WLAN can be obtained as the number of required subcarriers increase to $B_{total}/\Delta B$. Assume that we can calculate the minimal number of required subcarriers given N_u, which would be discussed later; then, the algorithm to calculate the capacity of patients is shown in Algorithm 1.

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Input: The maximal potential amount of bandwidth
       $B_{total}$, the bandwidth of one subcarrier $\Delta B$, and
       the total number of time slots $N_T$
Output: The maximal number of patients supported by
        the WLAN
1 Initialize $N_u = 0, S_{total} = 0, S_{(k)} = 0$, given that $S_{total}$
  is the total number of subcarriers of $N_T$ time slots;
2 Check whether $S_{total} \leq B_{total}/\Delta B$. If so, $N_u = N_u + 1$,
  go to step 3; Otherwise, go to step 4;
3 Given the $N_u$, allocate the bandwidth to attain the
  minimum of $\sum_{i=1}^{N_u} B_i^{(k)}$ at time slot $k (k = 1, 2 \cdots N_T)$;
4 $S_i^{(k)} =$
  $\max\left\{\left\lceil\left(\sum_{i=1}^{N_u} B_i^{(k)} + B_a^{(k)} - B^{(k-1)}\right)\Big/\Delta B\right\rceil, 0\right\}$, and
  $S_{total} = S_{total} + \sum_{i=1}^{N_u} B_i^{(k)}$;
5 $N_u$ is the maximal number of patients supported by this
  WLAN;
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Algorithm 1: Algorithm for the capacity of patients supported by the WLAN

Next, we attempt to calculate the minimal number of subcarriers given N_u, that is, to allocate bandwidth to attain the minimal $\sum_{i=1}^{N_u} B_i^{(k)}$ at any time slot k. The problem of minimizing $\sum_{i=1}^{N_u} B_i^{(k)}$ can be solved by an algorithm based on genetic theory [6], shown in Algorithm 2. Cartwright et al. in [6] show that the result of Algorithm 2 would converge to the global optimum with a probability of 1 assuming that the number of generations increases to infinite; this assumption does not hold in reality. In reality, after a finite number of generations, the Algorithm 2 must stop, and the result of Algorithm 2 may have an error in comparison with the exact global optimum. Given the result R and the exact optimum E, the relative error of this result is defined as $|R - E|/E$.

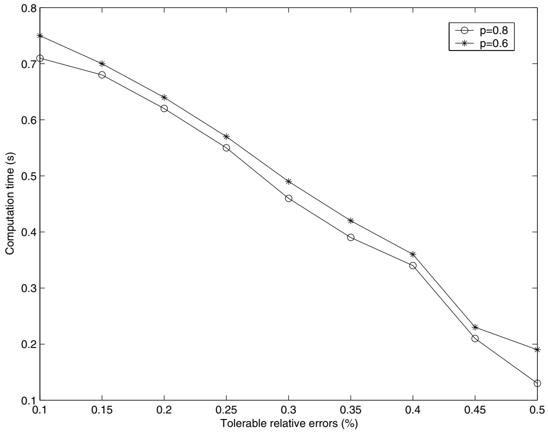

Fig. 2. Computation time vs. tolerable relative errors

IV. SIMULATION AND DISCUSSION

The parameters in the simulation are as follows: $N = 10000$; ΔB=0.8Mbps; $a_i^{(k)}$=800kbps; T_c=0.1s; $\Delta T_1 = 0.5T_c$; $\Delta T_2 = T_c$; $B_a^{(k)}/\Delta B \sim B(N_u, p)$, where $B(\cdot)$ represents a binomial distribution and p represents the probability of a subcarrier being occupied for video conferences. In Algorithm 2, $N_0 = 30$, $p_f = 0.05$, $p_c = 0.2$, and $p_m = 0.05$ [6].

Firstly, we discuss the total computation time of Algorithm 1 and Algorithm 2. The computation time depends on the tolerable relative errors of the obtained optimum. The computation time with our proposed scheme for various tolerable relative errors is shown in Fig.2. As expected, with the rise of tolerable relative errors, the computation time decreases. Now that the healthcare monitoring system is to assist healthcare staff to monitor patients, the computation time is acceptable in view of the time for a staff to take actions on patients (Usually a few seconds or even minutes).

Secondly, based on Algorithm 1 and Algorithm 2, we can obtain the capacity of patients supported by WLAN in view of EMI. Then, we compare it with the capacity without considering EMI constraints. The capacity of patients for various probability p and for various memory sizes M^{max} are shown in Fig.3. As shown in Fig.3, a small probability p corresponds to a larger capacity of patients. In addition, without considering EMI, the number of patients supported by the system would be overestimated. For a hospital, once the probability p is estimated by statistics, the capacity of patients supported by the WLAN can be estimated with our algorithm;

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Input: The optimization problem with the objective of $\sum_{i=1}^{N_u} B_i^{(k)}$
Output: The result of this algorithm, $\overline{B}^{(k)} = \left[B_1^{(k)}, B_2^{(k)}, \cdots B_{N_u}^{(k)}\right]$
1 We randomly select $N_0$ of $\overline{B}^{(k)}$ from the set of $\overline{B}^{(k)}$ that satisfy all the constraints of equation (3); we denote them as $\overline{B}_{(1)}^{(k)}, \overline{B}_{(2)}^{(k)}, \cdots \overline{B}_{(N_0)}^{(k)}$ ;
2 Order all the $\overline{B}_{(j)}^{(k)} (j = 1, 2, \cdots N_0)$ for an ascending order of objective function $\sum_{i=1}^{N_u} B_i^{(k)}$, and we denote ordered $\overline{\overline{B}}_{(j)}^{(k)}$ as $\overline{\overline{B}}_{(1)}^{(k)}, \overline{\overline{B}}_{(2)}^{(k)}, \cdots, \overline{\overline{B}}_{(N_0)}^{(k)}$;
3 Set the fitness function as $f_j = fitness(\overline{\overline{B}}_{(j)}^{(k)}) = p_f (1 - p_f)^{j-1} (j = 1, 2 \cdots N_0)$, where $0 \leq p_f \leq 1$ ;
4 Calculate the probability $p_j = f_j \Big/ \sum_{j=1}^{N_0} f_j$, and we reselect $N_0$ of $\overline{B}^{(k)}$ from the set of $\overline{\overline{B}}_{(1)}^{(k)}, \overline{\overline{B}}_{(2)}^{(k)}, \cdots, \overline{\overline{B}}_{(N_0)}^{(k)}$, with the probability of $p_j$ to select $\overline{\overline{B}}_{(j)}^{(k)}$. The same $\overline{\overline{B}}_{(j)}^{(k)}$ is allowed to be selected multiple times, and we denote the reselected group as $\overline{\underline{B}}_{(1)}^{(k)}, \overline{\underline{B}}_{(2)}^{(k)}, \cdots, \overline{\underline{B}}_{(N_0)}^{(k)}$;
5 With a probability $p_c$ of inheritance, we generate the next generation of $\overline{\underline{B}}_{(j)}^{(k)}$ according to $\overline{\overline{\underline{B}}}_{(i)}^{(k)} = C\overline{\underline{B}}_{(j_1)}^{(k)} + (1 - C)\overline{\underline{B}}_{(j_2)}^{(k)}$, where $\overline{\overline{\underline{B}}}_{(i)}^{(k)}$ denotes the next generation of $\overline{\underline{B}}_{(j)}^{(k)}$, $C$ is randomly selected between 0 and 1, $\overline{\underline{B}}_{(j_1)}^{(k)}$ and $\overline{\underline{B}}_{(j_2)}^{(k)}$ are a pair of $\overline{\underline{B}}_{(j)}^{(k)}$ selected for inheritance. If $\overline{\overline{\underline{B}}}_{(i)}^{(k)}$ satisfying all constraints of equation (3), then, we keep it in the next generation; otherwise, we reselect the pair of $\overline{\underline{B}}_{(j)}^{(k)}$ for inheritance until we get $N_0$ of $\overline{\overline{\underline{B}}}_{(i)}^{(k)}$;
6 With a small probability $p_m$, mutation of some $\overline{\overline{\underline{B}}}_{(i)}^{(k)}$ would occur. The process of mutation is $\overline{\overline{\underline{\underline{B}}}}_{(i)}^{(k)} = \overline{\overline{\underline{B}}}_{(i)}^{(k)} + M_{(i)}^{(k)} d_{(i)}^{(k)}$, where $M_{(i)}$ is a randomly selected step size and $d_{(i)}$ is a randomly selected direction of the $N_0$-dimension space formed by vectors $\overline{\overline{\underline{B}}}_{(i)}^{(k)}$. If $\overline{\overline{\underline{\underline{B}}}}_{(i)}^{(k)}$ satisfying all the constraints of equation (3), then, we keep it in this generation; Otherwise, we would regenerate $M_{(i)}^{(k)}$ and $d_{(i)}^{(k)}$ until we get a $\overline{\overline{\underline{\underline{B}}}}_{(i)}^{(k)}$ that satisfy all the constraints of equation (3);
7 Record $\overline{\overline{\underline{\underline{B}}}}_{(i)}^{(k)}$ that maximizes the objective function up to $k$th generation;
8 Repeat all the steps above, and output the $\overline{\overline{\underline{\underline{B}}}}_{(i)}^{(k)}$.
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Algorithm 2: Genetic theory based algorithm for bandwidth allocation

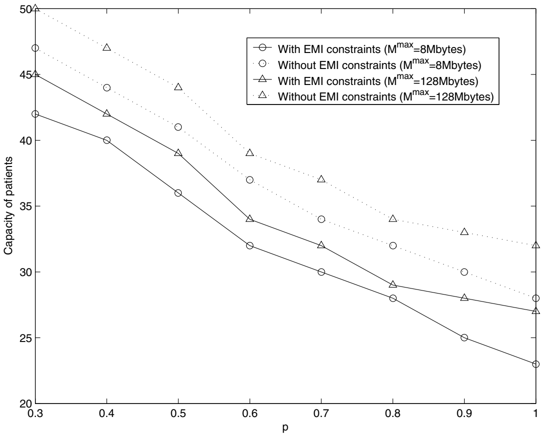

Fig. 3. Capacity of patients supported in the WLAN.

this information on capacity is necessary for the management of patients in wireless healthcare monitoring systems.

V. CONCLUSIONS

In this paper, we propose a bandwidth allocation scheme to enhance the capacity of patients in view of limited wireless bandwidth, QoS requirements of medical data transmission, and electromagnetic interference on medical equipments. Firstly, the problem of maximizing the capacity of patients is modeled as a dynamic programming problem. Then, we propose a genetic theory based algorithm to solve this programming problem. Finally, we analyze the computation time of our algorithm and obtain the capacity of patients supported by WLAN. Our work can provide some references for the management of patients in wireless healthcare monitoring systems.

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