Packet-Level Scheduling for Implant Communications Using Forward Error Correction in an Erasure Correction Mode for Reliable U-Healthcare Service

Ki-Dong Lee, Sang G. Kim, and Byung K. Yi

Abstract: **In u-healthcare services based on wireless body sensor networks, reliable connection is very important as many types of information, including vital signals, are transmitted through the networks. The transmit power requirements are very stringent in the case of in-body networks for implant communication. Furthermore, the wireless link in an in-body environment has a high degree of path loss (e.g., the path loss exponent is around 6.2 for deep tissue). Because of such inherently bad settings of the communication nodes, a multi-hop network topology is preferred in order to meet the transmit power requirements and to increase the battery lifetime of sensor nodes. This will ensure that the live body of a patient receiving the healthcare service has a reduced level of specific absorption ratio (SAR) when exposed to long-lasting radiation. We propose an efficient method for delivering delay-intolerant data packets over multiple hops. We consider forward error correction (FEC) in an erasure correction mode and develop a mathematical formulation for packet-level scheduling of delay-intolerant FEC packets over multiple hops. The proposed method can be used as a simple guideline for applications to setting up a topology for a medical body sensor network of each individual patient, which is connected to a remote server for u-healthcare service applications.**

Index Terms: **Erasure correction mode, forward error correction (FEC), medical body area network (MBAN) applications, medical body sensor network, scheduling, u-healthcare service, wireless sensor network.**

I. INTRODUCTION

The elderly population is expected to grow worldwide for next few decades; for example, by 2030, more than 22% people in European countries will be over 65 years old. This increase is expected to necessitate more public and private expenditure on health care; further, this increase in expenditure can encourage the development and application of smart information and communication technology [1], [2]. Recently, u-healthcare services have attracted considerable interest in the field of wireless networking and its applications industry. U-healthcare involves the use of information and communication technology to facilitate the exchange of health and medical information and services between patients and healthcare service providers. One of the most common applications of telemedicine is remote patient monitoring to carry out various measurements, such as those of blood pressure and heart rate. Remote patient monitoring enables the measurements to be carried out wherever a communication link established and thus, reduces the need for patients to visit health clinics; as a result, the quality of life of the patients, particularly the elderly, is improved.

In a recent paper [3], Chen, Gonzalez, Vasilakos, Cao, and Leung analyzed a wide range of technology trend in body area network (BAN) and its applications, including an overview of BAN, detailed sensor and communication technologies and issues related to BAN research and development. The design reliable and energy-efficient protocols is an interesting and important challenge [4]–[6]. Each sensor/communication node formed in a wireless BAN is run by a small battery [7], [8]. The in-body (present inside the body) and on-body (present on the body) nodes should be designed such that the nodes are small and durable; further, the design should ensure that energy-efficient transmission scheduling is realized and that the daily lives of patients (both human beings and animals) are not affected or disturbed. The main aim of this study is the development of improved u-healthcare services for patients by adopting efficient scheduling methods that can reduce unnecessary power consumption as much as possible so that exposure of patients to harmful radiation can be avoided as much as possible. In this study, we consider a medical BAN with two on-body fusion centers on each body receiving u-healthcare, and we design an energy-efficient method for scheduling in-body nodes.

There are multiple types of traffic generated by the medical sensor nodes, and some types are delay tolerant whereas others are not. Scheduling of delay-tolerant traffic is relatively easier than that of delay-intolerant and time-critical traffic. The latter is more challenging because the requirements associated with scheduling are more stringent. In this study, we consider delay-intolerant traffic in a BAN. More specifically, we consider an efficient packet delivery method of traffic based on forward error correction (FEC) in an erasure correction mode (FEC/EC). To the best of our knowledge, the scheduling of FEC/EC packet delivery over multi-hop BAN has not been extensively studied. Developing the physical layer optimization for FEC/EC schemes is an interesting topic, but it is not the major focus of this paper. We develop a mathematical formulation for parameter optimization so that the desired scheduling for delivery of FEC/EC packets through multi-hop BANs can be realized. The proposed method is simple and efficient, and therefore, it can be used as a sim-

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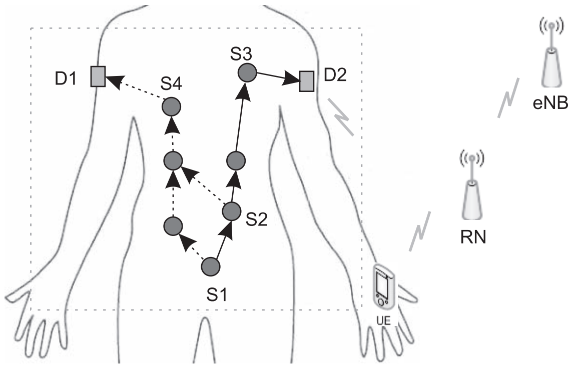

Fig. 1. U-healthcare service architecture based on a hierarchical telemedicine network with in-body (S1, S2, S3) and on-body (D1, D2) sensor nodes (or body control units, BCUs).

ple guideline for setting up a specific topology by identifying the possible locations for all in-body nodes and deciding the expected link quality in the BAN of each individual patient.

II. DESCRIPTION OF HEALTHCARE SERVICE MODEL: OPERATION AND CONTROL IN BODY AREA NETWORK

We consider a WBAN that transmits delay-intolerant data through multi-hop sensor/actuator nodes. However, the network model is different from that in IEEE 802.15 TG6 [8]. First, the network that we consider is a multi-hop network whereas the IEEE WBAN [8] is a single-hop network. Second, in IEEE 802.15 TG6, a star topology is considered, in which there is only one body control unit (BCU) for an individual BAN. In the case of BCU failure, the patient, as a dependent entity of u-healthcare service, may be unknowingly isolated. This may result in serious medical/engineering problems as well as prompt the patient to initiate legal action. Therefore, we are motivated to consider a generalized topology that may contain more than one BCU.

A. Source Coding for Traffic with Stringent Delay Constraints

Since wireless channels are normally error-prone, the use of source-coding methods, such as layered coding (LC) and FEC/EC, is preferred for reliably delivering the source information. Although LC and FEC/EC protect the source information from the noise of wireless channels, there is one different between them—the sub-bitstreams generated in FEC/EC have the same level of importance [9]. In the case of networks with no feedback control or for applications with very stringent delay constraints, the use of FEC/EC is more advantageous than that of LC is.In this study, we are interested in a WBAN supporting applications with very stringent delay constraints and therefore consider FEC/EC for delivering information over multiple hops.

B. Operation of Node of Body Area Network

An in-body source node (e.g., S1 in Fig. 1) receives certain information about a particular object of interest and generates a certain number of FEC/EC packets of the same size, each of which consists of n sub-streams. The packets are transmitted to the next node (e.g., S2 in Fig. 1), which acts as an in-body relay node (RN) and is set up by a given routing mechanism. These packets are eventually transmitted to one of on-body nodes; thus, they are transferred out of the body. If an in-body RN receives a packet, it checks how many sub-streams are decodable[1], by employing a simple parity check mechanism. If the number of successful substreams is less than a particular lower limit, say z, the packet transmission fails, otherwise the packet transmission succeeds. If the number is less than a threshold value y, the redundancy level will increase because of the generation of substreams so that the total number of valid ones for transmission becomes x. Once the packet reaches an on-body node or a BCU (e.g., D2 in Fig. 1), it is sent to the user equipment (UE), to an RN and further to the eNodeB (eNB).

C. Problem Description and Control Schemes

The healthcare provider identifies the positions where the body area sensor nodes can be located. The positions can be in-body or on-body. The healthcare provider shall simulate the channel quality of the links between the locations of the sensor nodes and shall store in each node the set of solutions corresponding to the different cases of possible channel quality. Once the in-body and on-body nodes are deployed, they measure the actual channel quality and analyzed the stored solution set to use the solution set that corresponds to the measured channel quality.

Before deploying the nodes in or on a body, the healthcare provider determines the average number of successful hops per packet and the average amount of transmit power per hop corresponding to a particular substream error rate. We now describe how these quantities are determined and later we discuss the objective and constraint(s) that we can define and how the control variables x and y should be selected accordingly. We consider the following three control schemes:

- Dual-variable controlled policy: (x, y)-policy
  - Scheme XY: Both x and y are optimized
- Single-variable controlled policy:
  - Scheme Y: This has a single control variable y where x is given by a fixed value $\bar{x}$ that can be updated regularly but not as frequently as y is updated.
  - Scheme X: This has a single control variable x, where y is given by z (packet-failure indication value).

Fig. 2 shows the bitstream representation for the FEC/EC. We consider an original piece of information (e.g., an image) of length nk in bits. These bits are placed in a packet in the order shown in the lower part of the figure by using FEC. A packet consists of a certain number of substreams (or descriptions), say k, and a certain number of substreams of FEC code. Suppose that the sender node has sent this packet with k useful information substreams and that the receiver node has not received the kth substreams, namely, it has received $k - 1$ useful information substreams. Using the FEC codeword, the receiver node can completely recover the lost substream. In this study, we consider a method by which the receiver node delivers the packet with useful information substreams without recovering the lost substream(s) if the following condition is not satisfied: If the number of useful information substreams is greater than or equal to a threshold value y.

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[1] In this paper, a chunk of bits is said to be decodable if no error is detected by a given error detection scheme.

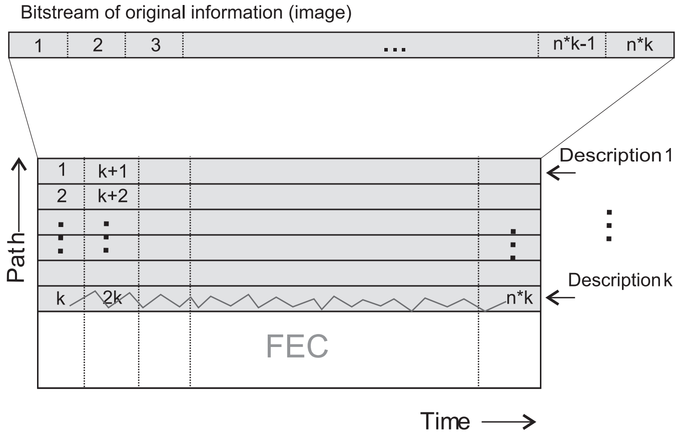

Fig. 2. Bitstream representation for the forward error control in an erasure correction mode.

III. ANALYSIS OF CONTROL SCHEMES FOR LOW-POWER HEALTHCARE SERVICE

Once sensor nodes are located inside or on the body, they initialize the link by identifying the transmit power P_{tx} [2] such that the target substream error probability will be achieved. If each node is configured to have the same target error probability, each link will experience the same level of error rate accordingly.

Let S_i denote the number of sub-streams that node i sends to the next node, $i+1$. Let $q_{j,k}$ denote the probability that a packet with $S_i = k$, which has been sent from the ith node to the $(i+1)$st node, has an erasure of j sub-streams (or descriptions) at the $(i+1)$st node.

$$q_{j,k} = \binom{k}{j} \beta^j (1-\beta)^{k-j}. \tag{1}$$

We consider a two-variable policy, (x, y)-policy, that can also be employed as a single-variable policy by keeping the value of one of the variables unchanged. When a receiver node receives a packet from the sender node, the receiver node checks whether the packet has been successfully received by any type of physical layer, data link layer, or cross layer mechanism. According to this policy, if the number of successful sub-streams within a packet that is received by a node is less than or equal to y (lower threshold), then the node shall rearrange the frame with the successful substreams such that the number of substreams in the packet becomes x (upper threshold). If the number of successfully received substreams within a packet is less than z, then the packet transmission is considered to have failed.

A. The Average Number of Successful Hops

Let $H(n; x, y, z)$ denote the average number of successful hops until the first failure of a packet that is transmitted from the source node with n useful sub-streams. In other words, $H(n; x, y, z)$ denotes the average number of nodes that a frame visits before the first failure of the packet that is transmitted from the source node with n valid sub-streams. [3]

In this policy, since the node that receives y or less but z or more successful substreams within a packet increases the redundancy by generating more substremas such that the frame has x substreams, we have

$$H(k; x, y, z) = H(x; x, y, z), \ k = z, \cdots, y. \tag{2}$$

Further, for $n = y+1, \cdots, x$, we have

$$\begin{aligned} H(n; x, y, z) &= \sum_{k=0}^{n-(y+1)} q_{k,n} \big\{ H(n-k; x, y, z) + 1 \big\} \\ &\quad + \sum_{k=n-y}^{n-z} q_{k,n} \big\{ H(x; x, y, z) + 1 \big\} \\ &\quad + \sum_{k=n-z+1}^{x} q_{k,n} 1 \\ &= \sum_{k=0}^{n-(y+1)} q_{k,n} H(n-k; x, y, z) \\ &\quad + \sum_{k=n-y}^{n-z} q_{k,n} H(x; x, y, z) \ + 1. \end{aligned} \tag{3}$$

Let

$$\mathbf{H}(x, y, z) = \left(\begin{array}{c} H(x; x, y, z) \\ H(x-1; x, y, z) \\ \vdots \\ H(y+1; x, y, z) \\ \hline H(x; x, y, z) \\ \vdots \\ H(x; x, y, z) \end{array} \right) \tag{4}$$

and let

$$\mathbf{A} \ = \left(\begin{array}{cccc|cc} q_{0,x} & q_{1,x} & \cdots & q_{x-y-1,x} & \cdots & q_{x-z,x} \\ 0 & q_{0,x-1} & \cdots & q_{x-y-2,x-1} & \cdots & q_{x-z-1,x-1} \\ \vdots & \ddots & \ddots & \vdots & & \vdots \\ 0 & \cdots & 0 & q_{0,y+1} & \cdots & q_{y-z+1,y+1} \\ \hline q_{0,x} & q_{1,x} & \cdots & q_{x-y-1,x} & \cdots & q_{x-z,x} \\ \vdots & \vdots & & \vdots & & \vdots \\ q_{0,x} & q_{1,x} & \cdots & q_{x-y-1,x} & \cdots & q_{x-z,x} \end{array} \right). \tag{5}$$

Then, we can rewrite this in a matrix form as follows

$$\mathbf{H}(x, y, z) = \mathbf{A}\mathbf{H}(x, y, z) + \mathbf{e}_{x-z+1} \tag{6}$$

where $\mathbf{e}_m = (1, \cdots, 1)^T$ of order m.

Given that $(\mathbf{I} - \mathbf{A})$ is invertible, (6) is rewritten as

$$\mathbf{H}(x, y, z) = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{e}_{x-z+1}. \tag{7}$$

Proposition 1: The matrix $(\mathbf{I} - \mathbf{A})$ is invertible $\forall \beta \in (0, 1)$.

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[2] In the subsequent sections of this paper, we only focus on packet-level transmission and thus only consider the number of substreams that each node has to handle.

[3] On the basis of the renewal theorem [11], the residual periods (e.g., the period from the first failure to the second failure) can be analyzed in the same way.

Proof: (Abbreviated) The matrix $(\mathbf{I}-\mathbf{A})$ is invertible because each element of $\mathbf{H}(x,y,z)$ is not diverging for $\beta\in(0,1)$. (Some related concept is available in [10]) □

Proposition 2: The average number of successful hops per packet rearrangement (i.e., increase in redundancy), $H(x;x,y,z)$ is strictly increasing in x for any given y and z such that $z\le y\le x$.

Proof: (Abbreviated) We have $H(x+1;x+1,y,z)=\sum_i b_i$, $H(x;x{+}1,y,z)=\sum_i b_i-(b_1-a_1)$, and $H(x;x,y,z)=\sum_i a_i$. Therefore, we have $H(x+1;\cdot,\cdot,\cdot)>H(x;\cdot,\cdot,\cdot)$ and $H(x;x+1,\cdot,\cdot)>H(x;x,\cdot,\cdot)$. This yields $H(x+1;x+1,y,z)>H(x;x,y,z)$. □

Proposition 3: The average number of successful hops per packet, $H(x;x,y,z)$, is strictly increasing in y.

Proof: Suppose that m substreams are valid in the packet received at a relay node, and consider the following two cases: $y=y_0$ (case 1) and $y=y_0+1$ (case 2) for any $y_0\ge z$. If $m>y_0+1$, then the probabilities that the packet fails in the next hop are the same for both the cases. However, if $m=y_0$, the failure probability is equal to $\sum_{k=0}^{z-1}q_{k,y_0}$ in case 1 but is equal to $\sum_{k=0}^{z-1}q_{k,x}$ in case 2.

Because the failure probability in case 1 is greater than that in case 2, i.e.,

$$\sum_{k=0}^{z-1}q_{k,y_0}>\sum_{k=0}^{z-1}q_{k,x},\tag{8}$$

the number of hops traversed by a packet in case 2 is larger than that in case 1. This means that the number of successful hops per packet is strictly increasing in y. □

B. The Average Transmit Power

Let $P(n;x,y,z)$ denote the average transmit power that a packet starting with n substreams at a sensor node (source node) consumes during the total hops it makes under (x,y) policy. Thus, the average amount of transmit power per packet per hop can be approximated as follows

$$P_H(x,y)\simeq\frac{P(x;x,y,z)}{H(x;x,y,z)}.\tag{9}$$

Let

$$\mathbf{P}(\mathbf{x},\mathbf{y},\mathbf{z})=\left(\begin{array}{c}P(x;x,y,z)\\ P(x-1;x,y,z)\\ \vdots\\ P(y+1;x,y,z)\\ \hline P(x;x,y,z)\\ \vdots\\ P(x;x,y,z)\end{array}\right),\tag{10}$$

and let

$$\mathbf{b}(\mathbf{x},\mathbf{y})=\left(\begin{array}{c}x\\ x-1\\ \vdots\\ y+1\\ \hline x\\ \vdots\\ x\end{array}\right).$$

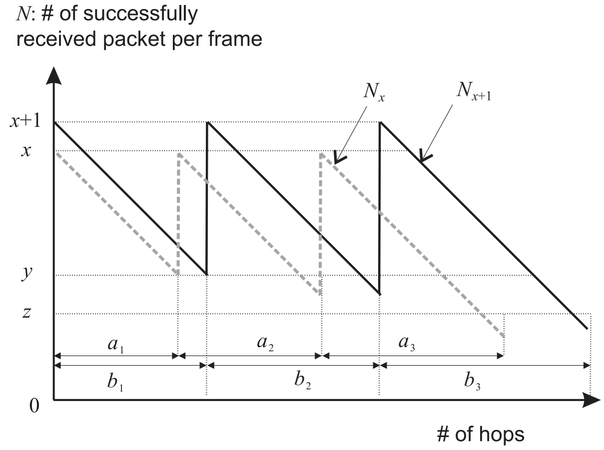

Fig. 3. Sample paths in the case of (x,y) policy. The decreasing behavior does not appear to be necessarily linear.

Then, we obtain the following recursive relation

$$\mathbf{P}(\mathbf{x},\mathbf{y},\mathbf{z})=\mathbf{A}\mathbf{P}(\mathbf{x},\mathbf{y},\mathbf{z})+\mathbf{b}(\mathbf{x},\mathbf{y}).\tag{11}$$

Thus,

$$\mathbf{P}(\mathbf{x},\mathbf{y},\mathbf{z})=(\mathbf{I}-\mathbf{A})^{-1}\mathbf{b}(\mathbf{x},\mathbf{y}).\tag{12}$$

By taking the first element of the above vector $\mathbf{P}(\mathbf{x},\mathbf{y},\mathbf{z})$, we can find the average power consumption when a packet consists of x substreams at the source node.

Proposition 4: $P(x;x,y,z)$ is strictly increasing in x.

Proof: (Abbreviated) Referring to Fig. 3, we can obtain the following expressions

$$P(x+1;x+1,y,z)=\int_0^{b_1+\cdots+b_4}S_{x+1}dt,\tag{13}$$

$$P(x;x+1,y,z)=\int_{b_1-a_1}^{b_1+\cdots+b_4}S_{x+1}dt,\tag{14}$$

and

$$P(x;x,y,z)=\int_0^{a_1+\cdots+a_4}S_x dt.\tag{15}$$

As a result, we have

$$P(x+1;x+1,y,z)>P(x;x+1,y,z)\tag{16}$$

and

$$P(x;x+1,y,z)>P(x;x,y,z).\tag{17}$$

This yields $P(x+1;x+1,y,z)>P(x;x,y,z)$. □

Proposition 5: $P(x;x,y,z)$ is strictly increasing in y.

Proof: (Abbreviated) Because the packet failure probability decreases as y increases and because more power is necessary for each node to transmit packets having great lengths due to more frequent increase in redundancy, the average transmit power per packet per hop increases. □

Table 1. Parameter values used in numerical examples.

Parameter	Value	Parameter	Value
η_P	z–1000	η_H	> 10
x_U	16, 32	$\bar{x}$	12
z	6	d	50–100 (mm)
d_0	50 (mm)	P_{tx}	≤ 1 (mW)
N_o	10^{-11} (W/Hz)	R	50 (Kbits/s)

IV. OPTIMUM TRANSMISSION SCHEDULING

We consider the following two types of scheduling problems for the two transmission policies: minimizing the average power consumption per successful hop and maximizing the average number of successful hops. The healthcare provider should identify the positions where each in-body node should be located and simulate the link quality necessary for achieving the possible parameter optimization whose results, which constitute the optimized parameter setup, can be stored in the in-body nodes so that the nodes can use the results to facilitate efficient FEC/EC delivery without consuming extra batter power for actual online scheduling.

A. Minimization of the Average Transmit Power Consumption per Successful Hop

The role of the following problem (PH) is to find (x, y) such that the average transmit power consumption per successful hop is minimized. In (PH), the average number of successful hops per packet is lower-bounded by a threshold η_H.

$$\begin{aligned} (PH) \quad & \text{Minimize} \quad && P_H(x, y) && (18)\\ & \text{subject to} \quad && H(x; x, y, z) \geq \eta_H, && (19)\\ & && (x, y) \in S(x_U, z) \end{aligned}$$

where $S(x_U, z) = \{(x, y) \mid z \leq y \leq x \leq x_U\}$.

B. Maximization of the Average Number of Successful Hops

The role of (HP) is to maximize the average number of successful hops per packet subject to the constraint that the average transmit power per hop is lower-bounded by a given threshold η_P.

$$\begin{aligned} (HP) \quad & \text{Maximize} \quad && H(x; x, y, z) && (20)\\ & \text{subject to} \quad && P_H(x, y) \leq \eta_P, \\ & && (x, y) \in S(x_U, z) \end{aligned}$$

V. PERFORMANCE EVALUATION

A. Setup for Evaluation

We use the parameter values specified in Table 1. Fig. 4 shows how much transmit power (mW) is needed to achieve a data rate of 50 Kbits/s at the target substream error probability of 0.01 and path loss exponent $\alpha = 6$, which corresponds to deep tissues.

B. Results and Discussion

Fig. 5 shows the average transmit power per hop versus the packet loss probability (PLP). From the results, we observe that the optimal solutions for the respective schemes are not affected by the value of x_U. This implies that the constraint $x \leq x_U$ is non-binding at the optimum, namely, the optimal x and y of each problem are smaller than 16; as a result, any increase in x_U improves neither the optimal solution of (x, y) nor the objective value of each problem. It is also observed that as PLP increases, the schemes Y and X become infeasible much faster than the other schemes do. This implies that schemes Y and X, which are single-variable-controlled policies, are not attractive in terms of flexibility in utilizing radio resources and cause the transmit power performance to be poor under bad channel conditions.

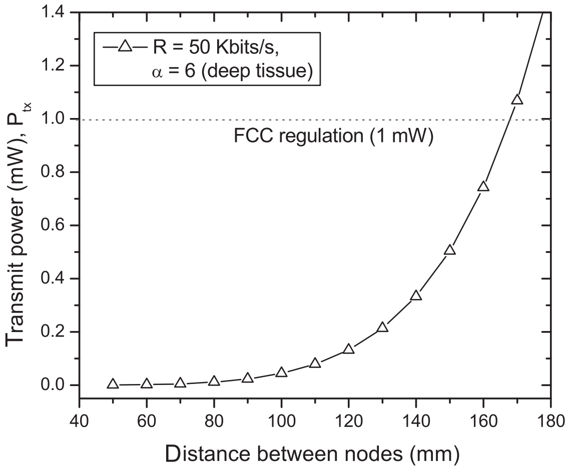

Fig. 4. Transmit power (mW) for a target sub-stream error probability of 0.01 vs. node-to-node distance (mm).

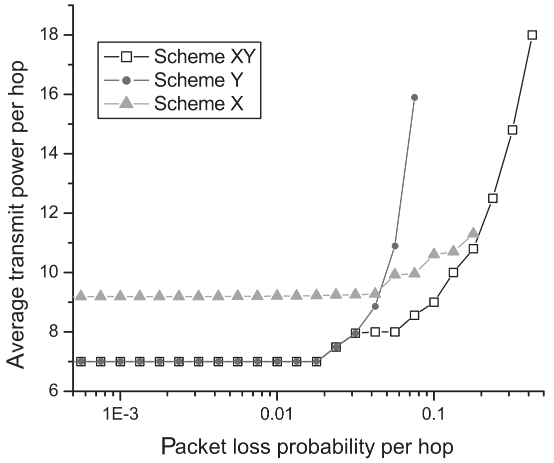

Fig. 5. Average transmit power consumption (measured in sub-streams) vs. packet loss probability.

Even though scheme Y is a single-variable controlled scheme, when the PLP is small, the power consumption is comparable to that in the case of scheme XY; however, a significant difference between the two schemes is observed when PLP is large.

Fig. 6 shows the average number of successful hops per packet versus the PLP. Usually, the average number of successful hops per packet decreases as the PLP increases when the control variables are optimized. It is observed that the perfor-

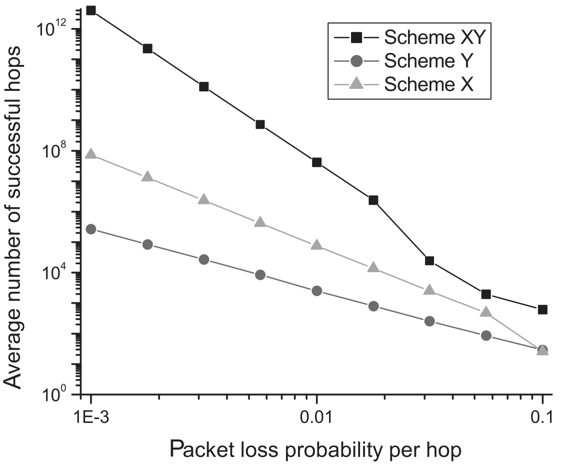

Fig. 6. The average number of successful hops vs. packet loss probability.

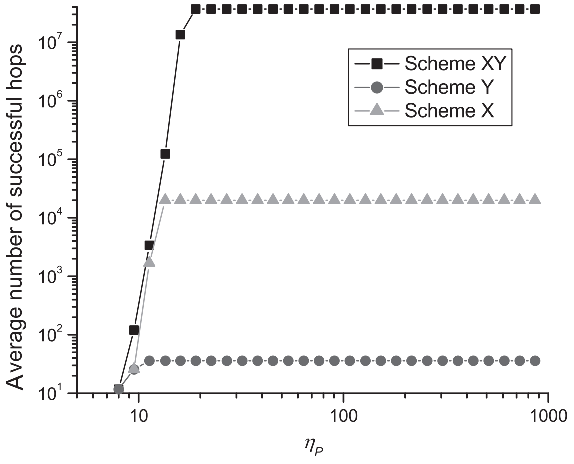

Fig. 7. Average number of successful hops vs. power consumption threshold η_P.

mance of the scheme XY is considerably better than the other two single-variable-controlled schemes; in schemes Y and X, the power consumption levels are so high that the power constraint is mostly binding at the optimum even though the other constraints of (HP) are not binding.

Fig. 7 shows the average number of successful hops per packet versus the power consumption threshold η_P. In the cooperative diversity techniques, the power consumption constraint of (HP) is not binding, whereas in the schemes that are more sensitive to the power consumption threshold η_P, the power consumption constraint is binding at the optimum.

C. Computational Complexity

The scheduling problems presented in subsections IV-A and IV-B require matrix computations. When the healthcare service provider plans to deploy the BSUs on and in a patient body, no real-time computation of matrices is required for scheduling; this is one of the most important practical advantages of this u-healthcare application. This method can also be adopted in cases that require real-time online computing if BSUs are capable of performing low-level of computations which are the common capabilities of today's sensor nodes. In such cases, it is imperative to use an efficient scheduling algorithm to determine the values of two parameters, namely, the maximum level of redundancy x and minimum level of redundancy y. The scheduling operation can be performed in a distributed manner or in a centralized manner, depending on which node(s) will perform the scheduling task and how the node(s) will perform the tasks. The determination of the operational architecture and signaling protocols is interesting but is beyond the scope of this paper.

Irrespective of the number of nodes that get involved with the scheduling, the search algorithm should carry out matrix computations. One of possible ways for reducing the computational burden is to reduce the deviation of the values of the two parameters; if there is no concern about the cost corresponding to each event of increase in the redundancy, the power cost will increase as the deviation between x and y increases. On the basis of this property, we can select a fairly small matrix $\mathbf{A}$ to obtain $\mathbf{H}(\cdot)$ and $\mathbf{P}(\cdot)$. Thus, we can reduce the computational burden.

VI. CONCLUSIONS

In this study, we have considered the applications of wireless networking technologies in u-healthcare services so that the peripheral devices of patients receiving healthcare services can be connected to a server or to the healthcare service provider. More specifically, we have considered an efficient low-power packet-level delivery method for the delivery of delay-intolerant data packets in a medical body area network using forward error correction in an erasure correction mode (FEC/EC). The main design targets were the average transmit power per successful hop (measured in packets) and the average number of successful hops until packet failure. If the proposed method can be modified, a software application can be developed that is based on the modified method and that can help healthcare practitioners to easily determine the suitable topologies of medical body area networks of individual patients. The topologies can be determined before deploying the sensor nodes of the body area networks by identifying the possible locations for in-body and on-body sensor nodes and by deciding the expected link quality between the nodes.

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