Entropy-maximization Based Adaptive Frequency Hopping for Wireless Medical Telemetry Systems

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ABSTRACT

In this paper, we propose an adaptive frequency hopping algorithm, entitled *robust adaptive frequency hopping* (RAFH), for increased reliability of wireless medical telemetry system (WMTS) under coexistence environment with non-medical devices. The conventional adaptive frequency hopping (AFH) scheme classifies channels into "good" or "bad" according to the threshold-based on-off decision, and uses good channels with a uniform hop probability. Unlike the conventional AFH scheme, RAFH solves a constrained entropy maximization problem and assigns each channel a different hop probability, which is a decreasing function of the measured PER. By adopting constrained entropy maximization, RAFH not only improves the average PER, but also reduces the PER fluctuation under dynamic interference environment. Our simulation studies show that RAFH outperforms the basic FH and the conventional AFH with respect to the PER under various scenarios of dynamic interference.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*; C.4 [**Performance of Systems**]: Reliability, Availability, and Serviceability

General Terms

Algorithms, Performance, Reliability

Keywords

Wireless medical telemetry system, frequency hopping spread spectrum, wireless coexistence, entropy maximization

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1. INTRODUCTION

Today's hospitals are deploying numerous devices over wires for various medical applications such as monitoring, diagnosis, and treatment. In order to reduce the cost and the time required to rewire hospitals and their equipments for plugging more devices, there exists an increasing demand for replacing wires by wireless technologies. This replacement not only reduce deployment cost, but also gives patients greatly increased mobility and comfort by releasing them from wired connection. In fact, major vendors are currently manufacturing commercial medical products based on wireless technologies [6, 9, 12].

With this necessity of wireless technologies in the healthcare community, recently there has been increasing research efforts in wireless medical networks, e.g., [1, 4, 11]. For successful migration to wireless technologies from wires in healthcare applications, we need to resolve several challenging issues. Most of all, how to guarantee the required reliability level of medical applications by wireless connection is a critical one. The main design goal of general wireless networks has been to improve network performance such as the average throughput. On the contrary, wireless medical networks ask for a high level of reliability while requiring moderate data rates. For example, a monitoring device for electrocardiogram (ECG) requires only a several Kb/s for its data rate, but demands for its dropout rate lower than a few seconds per hour.

In this paper, we study the problem of how to design a reliable communication scheme for wireless medical networks. In particular, as a prevalent application of wireless medical networks, we focus on *wireless medical telemetry system* (WMTS) that is used for monitoring a patient's health. Specifically, our technical contributions are as follows:

- In order to improve reliability of the conventional frequency hopping in the current WMTS, we propose an adaptive frequency hopping scheme, entitled *robust adaptive frequency hopping* (RAFH). We use the packet error rate (PER) as a metric for reliability of WMTS because PER is the main reason for the system dropout in the communication layer. The design rationale of RAFH is to exploit frequency diversity as much as possible, which is the main principle of spread spectrum. At the same time, RAFH restricts the total PER below a certain level for estimated interference. RAFH periodically measures the PER of each frequency channel.

- Then, if the total PER exceeds a certain threshold, RAFH updates the hopping probability by a constrained entropy maximization approach, which enables RAFH to exploit frequency diversity for mitigating random interference and to maintain the total PER below a given level for estimated interference. Our simulation study shows that RAFH reduces the average PER as well as PER fluctuation compared to the basic FH and the conventional AFH under various coexistence scenarios with other devices.

There exist quite a number of existing studies on adaptive frequency hopping, e.g., [7, 10]. A prevailing one is the adaptive frequency hopping scheme specified in the Bluetooth Standards [8]. Here, RAFH further exploits frequency diversity in order to provide increased reliability of WMTS under dynamic coexistence environment with other non-medical wireless devices.

The remainder of the paper is structured as follows. In Section 2, we provide background required for understanding available design options for reliable communication in WMTS. In Section 3, in order to improve the reliability of the conventional FHSS currently adopted in WMTS, we propose an adaptive frequency hopping scheme, called robust adaptive frequency hopping (RAFH). We evaluate the performance of RAFH in Section 4. The conclusion follows in Section 5.

2. BACKGROUND: DESIGN OPTIONS FOR WIRELESS MEDICAL TELEMETRY SYSTEMS

In this section, we provide background on design options for the communication scheme in WMTS.

2.1 Selection of the Operating Band: WMTS Bands or ISM Bands?

2.1.1 WMTS Bands

Wireless medical telemetry is defined as the remote monitoring of a patient's health through radio technology [5]. Previously, the US Federal Communications Commission (FCC) has permitted medical telemetry devices to operate on the following frequencies: vacant broadcast television channels 7–13 and 14–46 (174–216 MHz and 470–668 MHz), certain frequencies within the private land mobile radio service (PLMRS) in the 450–470 MHz band, and frequencies associated with the ISM bands of 902–928 MHz and 2.4–2.5 GHz. However, in March 1998, a TV station in Texas tested digital television broadcasting that severely interfered with the telemetry system at local hospitals. After this incident, the American Hospital Association (AHA)'s Medical Telemetry Task Force led the effort for defining wireless telemetry service and its spectrum options. As a consequence of this effort, the WMTS bands were created The WMTS bands include the following three separate frequency bands: 608–614 MHz (formerly TV channel 37), 1,395–1,400 MHz, and 1,429–1,432 MHz. With the creation of the dedicated WMTS bands, many hospitals upgraded their telemetry systems in order to operate in the WMTS bands, typically in the 608–614 MHz band.

While the introduction of the WMTS bands has eliminated the problem of competing with an in-band high definition television (HDTV) station, it did not inherently resolve the interference issues primarily because unintentional electromagnetic interference still exist in the dedicated WMTS bands [2]. Examples of unintentional interference sources are power lines, electrical motors, equipment power supplies as well as lightning strikes and electrostatic discharge. Another shortcoming of the WMTS bands is its small bandwidth. Even if a WMTS system could use the entire non-contiguous WMTS bands of 14 MHz, this bandwidth is substantially smaller than that of the ISM bands.

2.1.2 ISM Bands

The ISM bands were originally reserved internationally for the use of RF electromagnetic fields for industrial, scientific and medical purposes. Typically used ISM bands are 902–928 MHz (900 MHz band), 2,400–2,500 MHz (2.4 GHz band), and 5,725–5,875 MHz (5.8 GHz band). The 900 MHz band has been in limited medical telemetry use. The 2.4 GHz band is currently used by many manufacturers of medical telemetry systems. One crucial merit of the 2.4 GHz ISM band is a large contiguous bandwidth of 79 MHz, which increases the benefit of the spread spectrum technology for interference mitigation. One disadvantage of the ISM bands for WMTS is that they are unlicensed and are subject to interference from other devices such as IEEE 802.11 WLAN devices, Bluetooth, microwave ovens, and cordless telephones.

2.2 Spread Spectrum Technology: Frequency Hopping or Direct Sequence?

Spread spectrum refers to a wideband radio frequency technique originally used for the military purpose of secure mission-critical communication. In principle, the spread spectrum technology is designed to trade bandwidth efficiency for reliability. This tradeoff makes the overall transmission more reliable and robust against interference and noise. Furthermore, for any unintended receivers, the spread spectrum signal looks like background noise. This feature makes it very difficult for an unintended receiver to intercept or overhear the transmission.

There are two implementation options for spread spectrum, i.e., frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). DSSS is more suitable for providing high data rates, which made all the major vendors for IEEE 802.11 products select DSSS over FHSS for increasing their data rates. The main benefit of FHSS over DSSS is its robustness to strong interferers because avoiding interference by hopping rather than suppressing mitigates performance degradation. It is also no coincidence that the major manufacturers for WMTS in the ISM bands chose FHSS for their communication technology, for example, GE Healthcare (ApexPro FH) [6], Philips (IntelliVue Telemetry System) [9], and Welch Allyn (Micropaq) [12].

There are two implementation options for spread spectrum, i.e., frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS). FHSS uses a narrowband carrier that changes frequency in a pattern known to both the transmitter and the receiver. Both the sender and the receiver hop between frequencies based on the same pseudorandom pattern, and transfer data during each hop. Under proper synchronization, frequency hopping maintains a single logical channel. To an unintended receiver, FHSS appears to be short-duration impulse noise. Furthermore, even if the FHSS signal is corrupted by a narrowband interferer, the device can send data successfully once it hops to a new clear frequency channel. Thus, even when more and more frequency channels are corrupted by interference, FHSS does not completely fail but degrades gracefully.

3. AN EFFICIENT ADAPTIVE FREQUENCY HOPPING SCHEME FOR WMTS

In this section, we propose an adaptive frequency hopping scheme for WMTS, entitled *robust adaptive frequency hopping* (RAFH). By using a constrained entropy maximization approach, RAFH exploits frequency diversity in order to be robust against random interference while maintaining the total PER below a given threshold for estimated interference.

3.1 Network Model

Though our proposed algorithm, RAFH, can also be used in the WMTS bands, in order to fully benefit from spread spectrum, we mainly consider a wireless LAN (WLAN) structure for WMTS operating under FHSS in the 2.4 GHz ISM band. Each WLAN has an access point connected with a number of wireless medical devices. Data packets from a device are sent to the corresponding AP as a stream with a constant rate, which is general in telemetry applications [1]. Timing and hopping of every device in each AP is synchronized with the corresponding AP. Two kinds of interference sources are assumed to coexist with the proposed WMTS. The first one is the the standard frequency hopping (FH) interferer such as a legacy medical device and a bluetooth device. The other is a direct sequence (DS) interferers such as an IEEE 802.11 device.

Let M denote the total number of frequency channels available. Let p_i denote the probability that a given AP uses frequency channel i where $i = 1, \ldots, M$. Then, the hopping probability set $\mathbf{p}$ of the AP is given as follows:

$$\mathbf{p} = [p_1 \ldots p_M]^T,$$

where $\sum_{i=1}^{M} p_i = 1$. For example, a uniform hopping probability set $\mathbf{p} = [1/M \ldots 1/M]^T$ corresponds to the basic FH case where all the frequency channels are equally used. The PER of each frequency channel is measured for every interval of T seconds. The condition that the measured total PER exceeds a given threshold η is the triggering event for an update of the hopping probability $\mathbf{p}$. Let $n = 1, 2, \ldots$ denotes the time index for each PER measurement interval. Also, let $\widehat{PER}_i(n)$ denote the measured PER of frequency channel i at time n.

3.2 Design Rationale of the Proposed Adaptive Frequency Hopping Scheme

Adaptive frequency hopping based on PER measurement can be formulated as how to update the hopping probability $\mathbf{p}$ based on the measured PER for each channel as follows:

$$\mathbf{p}(n+1) = F\left(\mathbf{p}(n), \widehat{\mathbf{PER}}(n)\right), \tag{1}$$

where $\widehat{\mathbf{PER}}(n) := [\widehat{PER}_1(n) \ldots \widehat{PER}_M(n)]^T$. One example for the update rule $F(\cdot, \cdot)$ in (1) to implement an adaptive frequency hopping scheme is to avoid bad frequency channels determined by PER measurement as follows:

$$p_i(n+1) = \begin{cases} 1/M_{n+1}, & \text{if } \widehat{PER}_m(n) < PER_{th}\ ; \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

where M_{n+1} is the total number of frequency channels that satisfy $\widehat{PER}_i(n) < PER_{th}$. In fact, even though there are differences in details, many adaptive FH algorithms basically operate as given in (2). Hereafter, we denote (2) as the conventional AFH. The decision for channel condition in (2) is on-off based on measured PER: If the measured PER is below/above the threshold, the corresponding channel is considered good/bad. By this on-off decision, every bad channel is completely avoided while every good channel is equally treated regardless of its measured PER.

Another disadvantage of (2) is that, by completely avoiding bad channels, the conventional AFH in (2) will not be able to measure the PER of channels once they are classified into bad ones. One typical solution is to use a timer for bad channels: Once the PER of a channel is above the threshold, classify it into a bad channel for a duration of T_s. Then, after T_s, the decision on the channel will be reset and it will be used for hopping as if it were now a good channel. However, a potential problem of this solution is that the AFH scheme will severely fluctuate under dynamic interference environment. If the timer T_s is small compared to interference change, the PER of AFH will severely increase because the channel may still remain bad after the reset, which is a case of false positive. If the timer T_s is large compared to interference change, AFH will slowly respond to change in interference, which corresponds to a case of false negative. Since an appropriate value for the timer T_s depends on the dynamic characteristics of interference, a single, pre-determined value for T_s cannot work in general.

Our design rationale of RAFH is to assign the hop probability by taking into account the magnitude of the measured PER. First, based on the measured PER which accounts for current interference, the hop probability should be assigned so that the total PER is below a given threshold. This condition imposes an explicit PER constraint in the formulation of RAFH in the next section. However, a constraint on the total PER based on the current measurement is not sufficient because it does not provide robustness against randomness in interference caused either by an error in the measure PER or by change in interference. Thus, in order to compensate for the PER measurement error and combat for unknown future interference, the hop probability should be randomized as much as possible to exploit frequency diversity, which is the main principle of FHSS.

3.3 Description of RAFH: An Entropy Maximization Approach

One reasonable approach for realizing our design rationale is to maximize the entropy of the hop probability $\mathbf{p}$ while satisfying the total PER constraint with respect to the measured PER. With a prespecified PER threshold ξ and the measured PER in the n-th interval, the total PER can be restricted if the updated hopping probability $\mathbf{p}(n+1)$ satisfies $\sum_{i=1}^{M} \widehat{PER}_i(n) p_i(n+1) \leq \xi$. Thus, the overall entropy maximization problem for update of the hopping probability $\mathbf{p}$ is given as follows: [1]

$$\begin{aligned} &\text{maximize } \left\{ -\sum_{i=1}^{M} p_i(n+1) \log p_i(n+1) \right\} \\ &\text{subject to } A\mathbf{p}(n+1) \leq \xi \\ &\sum_{i=1}^{M} p_i(n+1) = 1, \end{aligned} \tag{3}$$

where $A = [\widehat{PER}_1(n) \ldots \widehat{PER}_M(n)]$. As a simple example, consider the case of no constraint on the average PER in (3). In this case, entropy maximization will give a uniform distribution of $\mathbf{p}(n+1) = [1/M \ldots 1/M]^T$, which matches the intuition that every frequency should be equally used when no information on interference is available. When there is a PER constraint, the entropy maximization approach will randomize the distribution of $\mathbf{p}$ as much as possible while satisfying the constraint on the total PER.

To further demonstrate how the constrained entropy maximization works, we show an illustrative example when $M = 4$ and $A = [0.14\ 0.16\ 0.18\ 0.2]$. When the PER threshold $\xi = 0.15 < \sum_{i=1}^{M} a_i/M = 0.17$, we have $\mathbf{p} = [0.65\ 0.24\ 0.08\ 0.03]^T$. If the conventional AFH scheme in (2) were applied to this case, the

[1] Note that the nonnegativity constraint on p_i, i.e., $p_i \geq 0, \forall i$, does not need to be included because of the problem structure. The optimal solution for (3), denoted by $\mathbf{p}^*$, will automatically sastify the nonnegativity constraint, which can be verified by (13).

hopping probability would be $\mathbf{p} = [1\ 0\ 0\ 0]^T$. Hence, compared to (2), the entropy maximization approach exploits more frequency diversity with a different weight on each channel, which depends on the measured PER. When $\xi = 0.2 > \sum_{i=1}^{M} a_i/M = 0.17$, we have $\mathbf{p} = [0.25\ 0.25\ 0.25\ 0.25]^T$, which corresponds to the conventional frequency hopping.

The overall RAFH algorithm, which substantiates the idea of the constrained entropy maximization approach, is given in Algorithm 1. In every interval of T, RAFH measures the PER of each frequency channel as well as the total PER. If the total PER exceeds a certain threshold, the loop for updating the hopping probability $\mathbf{p}$ is triggered. When the PER constraint is feasible by the feasibility test in Line 21 of Algorithm 1, RAFH updates the hop probability $\mathbf{p}$ by maximizing the entropy of $\mathbf{p}$ while satisfying a constraint on the total PER for estimated interference as in Line 23 of Algorithm 1. If the PER constraint is infeasible, the situation may be too serious to be resolved by adaptation in the physical layer alone. Hence, the serious interference situation is reported to the higher layers which may deal with it. At the same time, RAFH updates the hop probability set $\mathbf{p}$ so that only top K frequency channels are uniformly used, i.e., $p_i = 1/K$ if $i \in S_K$ and $p_i = 0$ otherwise, where S_K is the set of frequencies with the top K PER.

Now, the remaining issue is how to devise an efficient algorithm for solving the constrained entropy maximization problem (3), which corresponds to Line 23 of Algorithm 1. The problem (3) can be equivalently formulated as minimization of the negative entropy with a constraint as follows:

$$\begin{aligned} &\text{minimize } f(\mathbf{p}) \equiv \sum_{i=1}^{M} p_i \log p_i \\ &\text{subject to } A\mathbf{p} \le \xi \\ &\sum_{i=1}^{M} p_i = 1. \end{aligned} \tag{4}$$

In order to solve (4) efficiently, we rely on the convex optimization theory [3]. First, we check the feasibility of (4). By inspection, we can easily notice that the problem (4) is infeasible if $a_{min} := \min a_i > \xi$. We will discuss this infeasible case later and tentatively assume that $a_{min} := \min a_i \le \xi$. The constrained convex optimization problem (4) can be efficiently solved by using Lagrangian duality [3]. The basic idea of Lagrangian duality is to take account of the constraints in an convex optimization problem by augmenting the objective function with a weighted sum of the constraints. The Lagrangian L for (4) is given as follows:

$$L(\mathbf{p}, \lambda, \nu) = \sum_{i=1}^{M} p_i \log p_i + \lambda(A\mathbf{p} - \xi) + \nu \left(\sum_{i=1}^{M} p_i - 1 \right), \tag{5}$$

where λ and ν are called Lagrange multipliers. Now, we refer to the original optimization problem (4) as the primal problem. Then, the associated dual function $g(\lambda, \nu)$ of (4) is defined as the minimum value of the Lagrangian over all possible $\mathbf{p}$ as follows:

$$g(\lambda, \nu) = \inf_{\mathbf{p}} \left[\sum_{i=1}^{M} p_i \log p_i + \lambda(A\mathbf{p} - \xi) + \nu \left(\sum_{i=1}^{M} p_i - 1 \right) \right]. \tag{6}$$

In (6), the dual function $g(\lambda, \nu)$ is concave because it is the pointwise infimum of a family of affine functions of (λ, ν). Hence, the dual function yields lower bounds on the optimal value f^* of the

Algorithm 1 Robust adaptive frequency hopping (RAFH)

1: // Initialization
2: $\mathbf{p} \leftarrow [1/M \ldots 1/M]$
3: // PER estimation
4: Reset timer $t \leftarrow T$
5: $\mathbf{n}_t = (n_{1,t}, \ldots, n_{M,t}) \leftarrow \mathbf{0}$
6: $\mathbf{n}_e = (n_{1,e}, \ldots, n_{M,e}) \leftarrow \mathbf{0}$
7: **while** (True) **do**
8:     **if** current transmission uses frequency i **then**
9:         $n_{i,t} \leftarrow n_{i,t} + 1$
10:     **end if**
11:     **if** Transmission fails **then**
12:         $n_{i,e} \leftarrow n_{i,e} + 1$
13:     **end if**
14: **end while**
15: **for** $i = 1$ to M **do**
16:     $a_i = PER_i \leftarrow n_{i,e}/n_{i,t}$
17: **end for**
18: // update $\mathbf{p}$ if PER exceeds a given threshold η
19: **if** $PER = \sum_{i=1}^{M} n_{i,e} / \sum_{i}^{M} n_{i,t} > \eta$ **then**
20:     // feasibility test
21:     **if** $\min_i a_i \le \xi$ **then**
22:         // Update $\mathbf{p}$
23:         $\mathbf{p} \leftarrow \arg\min_{\mathbf{p}} \sum_{i=1}^{M} p_i \log p_i$ such that $\sum_{i=1}^{M} a_i p_i \le \xi$ and $\sum_{i=1}^{M} p_i = 1$
24:     **else**
25:         Alarm to the supervisory system
26:         $p_i = 1/K$ for the top K channels and $p_i = 0$ otherwise
27:     **end if**
28: **end if**

primal problem (4) for any $\lambda \ge 0$ and ν as follows:

$$g(\lambda, \nu) \le f^*.$$

Now, the best lower bound can be obtained from the dual function $g(\lambda, \nu)$ by formulating the dual problem as follows:

$$\begin{aligned} &\text{maximize } g(\lambda, \nu) \\ &\text{subject to } \lambda \ge 0. \end{aligned} \tag{7}$$

When the dual variables (λ, ν) are optimal for the dual problem (7), they are called optimal Lagrange multipliers, denoted by (λ^*, ν^*). Since the primal problem (4) is convex, the strong duality holds [3] and the optimal value for the dual problem (7) is equal to that of the primal problem (4). Hence, instead of solving the primal problem (4) directly, we can get the solution for (4) by solving the dual problem (7). Note that the dual problem (7) only have two variables, λ and ν, while the primal problem (4) has M variables.[2] Thus, it is much more efficient to solve the dual problem (7) than the primal problem (4) because it significantly reduces the computation and the complexity of the algorithm.

The remaining issue is to obtain an explicit expression for the dual function $g(\lambda, \nu)$ in (6). Since the Lagrangian L in (5) satisfies $\partial^2 L/\partial p_i^2 = 1/p_i > 0$ and $\partial^2 L/\partial p_i \partial p_j = 0$, L is positive definite and thus convex in $\mathbf{p}$. Hence, by plugging $\partial L/\partial p_i = \log p_i + 1 +$

[2]Usually, M is much larger than two. for example, $M = 79$ for FHSS in the 2.4 GHz ISM band.

$a_i\lambda + \nu = 0$ into (5), we obtain

$$\begin{aligned} g(\lambda,\nu) &= -\xi\lambda - \nu + \inf_{\mathbf{p}} \sum_{i=1}^{M} [p_i \log p_i + (a_i\lambda + \nu)p_i] \\ &= -\xi\lambda - \nu - \sum_{i=1}^{M} e^{-(a_i\lambda+\nu+1)} \\ &= -\xi\lambda - \nu - e^{-\nu-1} \sum_{i=1}^{M} e^{-a_i\lambda}. \end{aligned} \tag{8}$$

By using (8), the dual problem (7) can be rewritten as follows:

$$\begin{aligned} &\text{maximize } -\xi\lambda - \nu - e^{-\nu-1} \sum_{i=1}^{M} e^{-a_i\lambda} \\ &\text{subject to } \lambda \geq 0, \end{aligned} \tag{9}$$

In order to further simplify the dual problem (9), we maximize the objective function over ν for fixed λ by using $\partial g(\lambda,\nu)/\partial\nu = 0$. Then, we obtain

$$\nu = \log \sum_{i=1}^{M} e^{-a_i\lambda} - 1. \tag{10}$$

By substituting (10) into (9), we get

$$\begin{aligned} &\text{maximize } -\xi\lambda - \log\left(\sum_{i=1}^{M} e^{-a_i\lambda}\right) \\ &\text{subject to } \lambda \geq 0. \end{aligned} \tag{11}$$

After simple algebraic manipulation, (11) becomes

$$\begin{aligned} &\text{minimize } h(\lambda) \equiv \sum_{i=1}^{M} e^{(\xi - a_i)\lambda} \\ &\text{subject to } \lambda \geq 0. \end{aligned} \tag{12}$$

In the meantime, the necessary optimality condition for $\mathbf{p}$ can be obtained by differentiating the Lagrangian in (5) with respect to p_i as follows:

$$\frac{\partial L}{\partial p_i} = \log p_i + 1 + a_i\lambda + \nu = 0.$$

Finally, the optimal value for p_i, denoted by p_i^*, can be obtained as

$$p_i^* = e^{-(a_i\lambda^* + \nu^* + 1)}, \tag{13}$$

where λ^* and ν^* are optimal Lagrange multipliers obtained from (10) and (12).

Consequently, the overall entropy maximization problem of (4) can be solved once we solve (12). Since (12) is a convex optimization problem with only one variable λ, it can be efficiently solved by a gradient method. Let λ^* denote the optimal value of λ for (12). Then, if $h(\lambda)$ is strictly increasing, we have $\lambda^* = 0$. Otherwise, $h(\lambda)$ is strictly decreasing for $\lambda \leq \lambda^*$ and strictly increasing for $\lambda \geq \lambda^*$. Hence, (12) can be solved by a gradient algorithm starting from $\lambda = 0$. Now, what remains is how to check whether $\lambda^* = 0$ or not. The necessary and sufficient condition for $\lambda^* = 0$ is $dh(0)/d\lambda \geq 0$. From (12), $dh(0)/d\lambda = \sum_{i=1}^{M}(\xi - a_i)$. Hence, the condition for $\lambda^* = 0$ is $\xi > \sum_{i}^{M} a_i/M$. The overall algorithm for solving (4), which corresponds to Line 23 of Algorithm 1, is given in Algorithm 2.

As a remark, an interpretation of the condition on $\lambda^* = 0$ can be given as follows: If the uniform hop probability $\mathbf{p} = [1/M \ldots 1/M]^T$ satisfies the constraint in (4), then it will be the optimal solution to (4) because the uniform distribution maximizes entropy over all the distributions. In this case, the constraint in (4) will be inactive, i.e., $A\mathbf{p} < \xi$, which exactly corresponds to the obtained condition with the uniform distribution of $\mathbf{p}$. Furthermore, λ^* will be zero according to the KKT condition [3].

Algorithm 2 A dual algorithm for solving the entropy maximization problem in (4) (Line 23 of Algorithm 1)

```
INPUT: A, ξ, ε, α // ε is a stopping error and α is a step size
OUTPUT: p
C ← ξ − A; // C = [c_1 ... c_M]^T := [ξ − a_1 ... ξ − a_M]^T, M by 1 column vector
λ ← 0; // Initial λ
if Σ_{i=1}^{M} c_i < 0 then
    while |Σ_{i=1}^{M} c_i e^{c_i λ}| > ε do
        λ ← λ − α Σ_{i=1}^{M} c_i e^{c_i λ}
    end while
end if
ν ← log Σ_{i=1}^{M} e^{−a_i λ} − 1
for i = 1 to M do
    p_i ← e^{−(a_i λ + ν + 1)}
end for
Return p
```

Table 1: Default values of parameters used in the simulation study.

Parameter	Value	Definition
M	79	Number of frequencies
η	0.2	RAFH-triggering PER threshold
ξ	0.2	Average PER threshold in RAFH
T	1000	Update interval for RAFH
T_s	1000	Reset timer for bad channels in AFH
ϵ	10^{-4}	Stopping error for Algorithm 2 in RAFH
α	0.1	Step size for Algorithm 2 in RAFH
γ	0.002	Poisson arrival rate of a DS interferer
μ	0.001	Geometric rate for the dwell time of a DS interferer

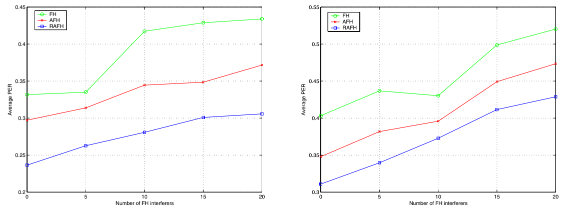
4. SIMULATION STUDY

4.1 Simulation Model

The simulation scenarios are designed to emphasize the dynamic pattern of interference. The FH sender hops around the 79 1-MHz frequency channels between 2.402 GHz and 2.480 GHz. The duration time for each hopping is fixed, which is considered as one time unit in the simulation. We consider the following two main sources of interference; the basic FH interference either from coexisting legacy medical devices or from Bluetooth devices, and the DS interference from IEEE 802.11 devices. A FH interferer interferes with probability one while a DS interferer with probability of 0.7. Each FH interferer hops over 79 1-MHz channels between 2.402 GHz and 2.480 GHz. Each DS interferer selects one from the following three non-overlapping channels; 2.402 – 2.424 GHz, 2.426 – 2.448 GHz, and 2.450 – 2.472 GHz. In each channel, a DS interferer is generated by the Poisson arrival with γ if the corresponding channel is not already occupied by another DS interferer. The dwell time of each DS interference traffic is geometrically distributed with μ. Hereafter, we denote the conventional AFH as AFH in short. Default values of parameters are given in Table 1.

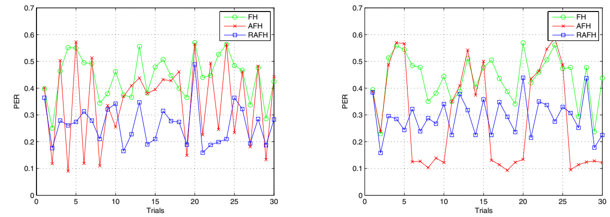
4.2 Simulation Results

First, we show the average PER with respect to the number of FH interferers in Fig. 1. The DS interferers are generated according the Poisson arrival with the default value of $\gamma = 0.002$ when the corresponding channel is not already occupied by a DS inter-



(a) When $\eta = \xi = 0.2$ (b) When $\eta = \xi = 0.3$

Figure 1: Average PER vs. number of FH interferers with random DS interferers.



(a) When $T_s = T$ (b) When $T_s = 5T$

Figure 2: Effect of the AFH reset timer T_s on PER fluctuation ($\gamma = 0.002$, $\mu = 0.001$, $\eta = \xi = 0.2$, and 10 FH interferers).

ferer. Also, the dwell time of each DS traffic follows a geometric distribution with $\mu = 0.001$. Each simulation run is performed for $30T$ $(= 30,000$ time units) and each point in Fig. 1 is an average over ten simulation runs. Figure 1 shows that RAFH outperforms the basic FH and the conventional AFH with respect to the PER under dynamic interference environment. As we can see from Fig. 1, the PER is larger than the threshold with both cases of RAFH and AFH. Since both of RAFH and AFH always try to lower the PER below the threshold, the PER would be smaller than the threshold if interference changed slowly. However, in the simulation, the DS interferers in the next interval can not be perfectly predicted because DS interferers arrive and leave in the next interval in a random manner. Furthermore, the random FH interferers increase the PER, which cannot be avoided because of its random hopping nature. Hence, these random aspects of interference are responsible for the additional amount of the PER over the threshold, which increases as the number of FH interferers increases.

Now, in order to show the effect of the reset timer T_s in AFH, we perform simulation for different values of T_s in Fig. 2, in which the number of FH interferers is ten and the third DS channel is not used for the DS interferers. With this interference setting, both the AFH and RAFH can maintain the PER below the threshold if they avoid interference by frequently using the third DS channel. When $T_s = T$, since AFH resets bad channels every update interval, the PER of AFH severely fluctuates around the threshold $(= 0.2)$ as given in Fig. 2(a) while that of RAFH remains around the threshold in most cases. Note that the additional amount of the PER over the threshold in RAFH is due to the random FH interferers. Unlike the fluctuation of AFH by the reset timer which happens every T_s, the fluctuation of RAFH happens only when the hop probability is updated due to the excessive PER over threshold. Note that RAFH is triggered only when the measured PER exceeds the threshold. When $T_s = 5T$, as shown in Fig. 2(b), the PER of AFH fluctuates approximately with a period of $5T$. Since the first and the second DS channels are active in most of the time, once these channels are considered bad in AFH, its PER remains quite a small value for $5T$ as those of $[5T, 10T]$, $[15T, 20T]$, and $[25T, 30T]$. However, after a duration of the reset timer $T_s = 5T$, AFH will reset the bad channels and use them as good ones, which will give a large value for the PER for a duration of $T_s = 5T$ as those of $[10T, 15T]$, and $[20T, 25T]$. On the contrary, as shown in Fig. 2(b), RAFH reasonably keeps its PER around the threshold.

5. CONCLUSION

In this paper, we have proposed an entropy-maximization based adaptive frequency hopping scheme, entitled RAFH, for reliable wireless medical telemetry. Our simulation study has shown that RAFH outperforms the basic FH and the conventional AFH with respect to the PER.

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