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Design of robust adaptive frequency hopping for wireless medical telemetry systems

K.-J. Park[1] *T.R. Park*[2] *C.D. Schmitz*[3] *L. Sha*[1]

[1]Department of Computer Science, University of Illinois, 201 N. Goodwin Avenue, Urbana, IL 61801, USA
[2]Samsung Advanced Institute of Technology (SAIT), Yongin, Republic of Korea
[3]Department of Electrical and Computer Engineering and the Beckman Institute, University of Illinois, Urbana, IL, USA
E-mail: kjp@uiuc.edu

Abstract: The authors propose an adaptive frequency hopping (AFH) algorithm, entitled robust adaptive frequency hopping (RAFH), for providing increased reliability of a wireless medical telemetry system (WMTS) under coexistence environment with non-medical devices. The conventional AFH scheme classifies channels into 'good' or 'bad' according to the threshold-based on–off decision by packet error rate (PER) measurement, and only uses good channels with a uniform hop probability. Unlike the conventional AFH scheme, RAFH is a novel technique, which solves a constrained entropy maximisation problem and assigns every channel a different hop probability as a decreasing function of the measured PER. The key novelty of RAFH over existing AFH schemes is that it reflects the relative channel condition by assigning non-uniform hop probabilities. By adopting constrained entropy maximisation, RAFH not only improves the average PER, but also reduces the PER fluctuation over time under a dynamic interference environment, both of which increase the reliability of WMTS. Through extensive simulation, we show that RAFH outperforms basic frequency hopping (FH) and the conventional AFH with respect to the PER under various scenarios of dynamic interference.

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 in more devices, there exists a surge in demand for replacing wires by wireless technologies [1–7]. This replacement not only reduces deployment cost, but also gives patients greatly increased mobility and comfort by releasing them from wired connections. Furthermore, the overall medical workflow can be much more convenient and effective in real time with wireless connections. In fact, major vendors are currently manufacturing commercial medical products based on wireless technologies [8–12]. Furthermore, the US healthcare industry is expected to be spending seven billion US dollars on deployment of wireless technologies by 2010 [13].

With this necessity of wireless technologies in the healthcare community, recently there has been increasing research efforts in wireless medical networks, for example, [1–4, 14–20]. 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 connections is a critical one [21–24]. 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 an electrocardiogram requires only a several Kb/s for its data rate, but demands for its dropout rate lower than a few seconds per hour [17, 25].

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 [26]. Our main concern is to propose a reliable communication scheme for WMTS under a coexistence environment with other non-medical devices. Specifically, our technical contributions are as follows:

We overview the design options for WMTS from the communication viewpoint. As two available options for the frequency band of WMTS, the dedicated WMTS bands and the unlicensed industrial, scientific and medical (ISM) bands are introduced. Then, we look into spread spectrum technology as the physical layer modulation/demodulation scheme for WMTS. We examine the differences between the frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS), which are the two possible implementations for spread spectrum. Based on this background study, FHSS is an adequate modulation/demodulation method for WMTS, which is currently adopted by the industry [8–10].

In order to improve reliability of the conventional frequency hopping (FH) in the current WMTS, we propose an adaptive frequency hopping (AFH) scheme, entitled robust adaptive frequency hopping (RAFH). First, we use packet error rate (PER) as a metric for the reliability measure of WMTS because PER is the main reason for 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 maximisation approach, which enables RAFH to exploit frequency diversity for mitigating random interference and to maintain the total PER below a given level for the estimated interference level. The key novelty of RAFH over existing AFH lies in the fact that RAFH assigns non-uniform hop probability by entropy maximisation, as a decreasing function of the measured PER. Note that the conventional AFH does not distinguish frequency channels as long as they exceed a given threshold, and assigns uniform hop probabilities for those channels with PER larger than the threshold. Our simulation study shows that RAFH reduces the average PER as well as PER fluctuation compared to basic FH and the conventional AFH under various coexistence scenarios with other devices.

There exist quite a number of existing studies on AFH, for example, [27–31]. A prevailing one is the AFH scheme specified in the Bluetooth Standards [32]. However, these existing studies on AFH did not fully exploit frequency diversity, which is the main principle of spread spectrum. Here, RAFH further exploits frequency diversity in order to provide increased reliability of WMTS under dynamic coexistence environments with other non-medical wireless devices. We will discuss this issue in Section 3.2 and explain in detail how RAFH can improve the system reliability.

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 system reliability of the conventional FHSS currently adopted in WMTS, we propose an AFH scheme, called RAFH. We evaluate the performance of RAFH in Section 4. The conclusion along with future research avenues follows in Section 5.

2 Background: design options for WMTS

In this section, we provide background on design options for the communication scheme in WMTS. First, we introduce the two most popular operating frequency bands, that is, the dedicated WMTS bands and the ISM bands. Second, since spread spectrum is a reliable modulation/demodulation scheme that is adequate for wireless medical networks, we introduce the two possible implementations for spread spectrum, that is, FHSS and DSSS.

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 [26]. 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 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 [33]. 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 for the purpose of providing hospital users dedicated RF spectrum for wireless medical telemetry operations [26]. The WMTS bands include the following three separate frequency bands: 608–614 MHz (formerly TV channel 37), 1395–1400 MHz, and 1429–1432 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. (Note that Europe has considered these bands and decided that they would not be available in Europe because of their use by other services.)

While the introduction of the WMTS bands has eliminated the problem of competing with an in-band high definition television station, it did not inherently resolve the interference issues primarily because unintentional electromagnetic interference still exists in the dedicated WMTS bands [21, 25]. Unintentional interference denotes signals emitted by electronic sources that are originally not supposed to broadcast. Examples of unintentional interference sources are power lines, electrical motors, equipment power supplies as well as lightning strikes and electrostatic discharge [21]. 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 ISM purposes. Typically used ISM bands are 902–928 MHz (900 MHz band), 2400–2500 MHz (2.4 GHz band) and 5725–5875 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 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 wireless LAN (WLAN) devices, Bluetooth, microwave ovens and cordless telephones.

2.2 Spread spectrum technology: FH or direct sequence?

Spread spectrum refers to a wideband radio frequency technique originally used for the military purpose of secure mission-critical communication [34]. In principle, the spread spectrum technology is designed to trade bandwidth efficiency for reliability. It consumes more bandwidth than narrowband technologies. Nevertheless, the tradeoff enables the sender to transmit a signal that is easier to detect at the intended receiver. Consequently, 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. Because of these properties, the spread spectrum technology naturally becomes promising for use in wireless medical networks, in which reliability is the most critical concern.

2.2.1 Frequency hopping spread spectrum: There are two implementation options for spread spectrum, that is, FHSS and 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 synchronisation, FH 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. Furthermore, AFH, which intelligently avoids bad frequencies, can further improve the performance.

2.2.2 Direct sequence spread spectrum: DSSS is another spread spectrum technology for modulation and demodulation in digital communication. DSSS modulates and demodulates the data signal to and from a signal with a much wider bandwidth. At the transmitter, a data stream of bit rate r_b is multiplied by a spreading signal of a pseudo noise (PN) sequence with chip rate r_c, which produces a chip stream with rate r_c. The ratio $g = r_c/r_b$ is called the processing gain. At the receiver, if the chip stream is multiplied by the same PN sequence, the original data stream can be recovered. If a different PN sequence is applied, the original data bit stream cannot be recovered and instead a noise-like random chip stream is generated. Thus, DSSS can significantly suppress a narrowband interference by spreading it out over the wide bandwidth. DSSS becomes more robust to narrowband interference as the processing gain increases. However, at the same time, DSSS requires more bandwidth for further spreading the data signal.

2.2.3 Comparison between FHSS and 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 [35]. The main benefit of FHSS over DSSS is its robustness to strong interferers because avoiding interference by hopping rather than suppressing mitigates performance degradation [36]. 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) [8], Philips (IntelliVue Telemetry System) [9] and Welch Allyn (Micropaq) [10].

3 RAFH for WMTS

In the previous section, we have given background on design options for the communication scheme of WMTS, and pointed out that FHSS is a reliable modulation/demodulation scheme for WMTS that is currently adopted in the industry. Now, our focus in the paper is on how to further increase the reliability of FH in WMTS under a coexistence environment with other non-medical wireless devices. Here, we introduce adaptiveness in the system that can efficiently avoid interference with the purpose of improving reliability by properly exploiting available information on interference.

In this section, we propose an AFH scheme for WMTS, entitled RAFH. By using a constrained entropy maximisation 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.

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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 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. An illustrative example is shown in Fig. 1. Typically, 5–10 monitoring devices are connected to each access point (AP) in medical telemetry applications [37]. Data packets from a device are sent to the corresponding AP as a stream with a constant rate, which is general in telemetry applications [17, 19]. It is assumed that self-interference among APs for the medical network is insignificant, which is realistic because medical networks are planned and deployed on a site-specific basis [21, 25]. (Self-interference among the same kind of networks is an important issue in Bluetooth because Bluetooth piconets are typically deployed without planning [28, 31]. In WMTS, self-interference might be a potential problem with overpopulated APs when devices connected to different APs exercise the same adaptive scheme. We will further elaborate on this issue by an illustrative example in Section III-C. A thorough treatment of self-interference is not in the scope of this paper. Our main focus is on how to deal with interference from other co-existing non-medical devices.) Timing and hopping of every device in each AP is synchronised with the corresponding AP. There is no interference among devices in the same AP, which can be realised by using a certain scheduling scheme in each AP. Two kinds of interference sources are assumed to coexist with the proposed WMTS. The first one is the standard 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 $\boldsymbol{p}$ of the AP is given as follows

$$\boldsymbol{p} = [p_1 \cdots p_M]^T$$

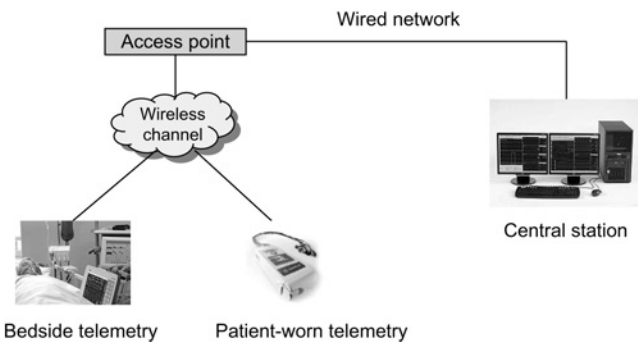

Figure 1 *Illustration of the unified medical telemetry system*

where $\sum_{i=1}^{M} p_i = 1$. For example, a uniform hopping probability set $\boldsymbol{p} = [1/M \ldots 1/M]^T$ corresponds to 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 $\boldsymbol{p}$. 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 RAFH

In wireless medical networks, the dropout rate of the system is a critical measure for reliability [19, 25]. In general, dropout can happen because of various failures in different layers. However, since the physical layer is the main concern in this paper, we consider the transmit packet error as the main reason for the system dropout. In order to reconstruct the transmitted signal at the receiver, at least a certain percentage of packets should be successfully received. Otherwise, the signal will not be successfully recovered, which corresponds to the dropout situation. Hence, the dropout rate can be quantified by the PER, that is, if the PER in an interval exceeds a certain level, the system is considered to be dropped out in the interval. Thus, in order to increase the system reliability by reducing the dropout rate, we not only need to reduce the average PER, but also need to lessen the fluctuation of the PER over time under dynamic interference environment.

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

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

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

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

where M_{n+1} is the total number of frequency channels that satisfy $\widehat{PER}_i(n) < PER_{\text{th}}$. 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. Hence, our motivation is that it would be better if we can reflect the magnitude of the measured PER and assign a non-uniform hop probability on each channel according to its 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 a dynamic interference environment. If the timer T_s is small compared to the interference change, the PER of AFH will severely increase because the channel may still remain bad after the reset, which is a case of a false positive. If the timer T_s is large compared to interference change, AFH will slowly respond to a change in interference, which corresponds to the case of a 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 simulation study in Section 4 verifies the PER fluctuation of AFH because of the effect of the timer T_s.

In order to reflect the channel condition more accurately than (2), 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 a change in interference. The measured PER is the sample mean of the actual PER and hence is a random variable even for a fixed value of the actual PER. Furthermore, the measured PER does not account for future interference, which can be changed because of random arrival and departure of interference source in the next interval. Thus, in order to compensate for the PER measurement error and combat for unknown future interference, the hop probability should be randomised as much as possible to exploit frequency diversity, which is the main principle of FHSS.

3.3 Description of RAFH: an entropy maximisation approach

One reasonable approach for realising our design rationale is to maximise the entropy of the hop probability $\boldsymbol{p}$ while satisfying the total PER constraint with respect to the measured PER. With a pre-specified PER threshold ξ and the measured PER in the nth interval, the total PER can be restricted if the updated hopping probability $\boldsymbol{p}(n+1)$ satisfies the following constraint

$$\sum_{i=1}^{M} \widehat{PER}_i(n) p_i(n+1) \le \xi$$

Thus, the overall entropy maximisation problem for update of the hopping probability $\boldsymbol{p}$ is given as follows. (Note that the non-negativity constraint on p_i, that is, $p_i \ge 0$, $\forall i$, does not need to be included because of the problem structure. The optimal solution for (3), denoted by $\boldsymbol{p}^*$, will automatically satisfy the non-negativity constraint, which can be verified by (13).)

$$\begin{aligned} &\text{maximise } H(\boldsymbol{p}(n+1)) \equiv -\sum_{i=1}^{M} p_i(n+1)\log p_i(n+1) \\ &\text{subject to } \boldsymbol{A}\boldsymbol{p}(n+1) \le \xi \qquad (3) \\ &\sum_{i=1}^{M} p_i(n+1) = 1 \end{aligned}$$

where $\boldsymbol{A} = [\widehat{PER}_1(n) \ldots \widehat{PER}_M(n)]$. As a simple example, consider the case of no constraint on the average PER in (3). In this case, entropy maximisation will give a uniform distribution of $\boldsymbol{p}(n+1) = [1/M \ldots 1/M]^T$, 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 maximisation approach will randomise the distribution of $\boldsymbol{p}$ as much as possible while satisfying the constraint on the total PER.

To further demonstrate how the constrained entropy maximisation works, we show an illustrative example when $M = 4$ and $\boldsymbol{A} = [0.14\ \ 0.16\ \ 0.18\ \ 0.2]$. When the PER threshold $\xi = 0.15 < \sum_{i=1}^{M} a_i/M = 0.17$, the hopping probability becomes $\boldsymbol{p} = [0.65\ \ 0.24\ \ 0.08\ \ 0.03]^T$ as shown in Fig. 2. If the conventional AFH scheme in (2) were applied to this case, the hopping probability would be $\boldsymbol{p} = [1\ \ 0\ \ 0\ \ 0]^T$. Hence, compared to (2), the entropy maximisation approach exploits more frequency diversity with a different weight on each channel, which depends on the measured PER. When $\xi = 0.2 > \sum_{i=1}^{M} a_i/M = 0.17$, as shown in Fig. 2, we have $\boldsymbol{p} = [0.25\ \ 0.25\ \ 0.25\ \ 0.25]^T$, which corresponds to the basic FH. Another benefit of RAFH over the conventional AFH is that RAFH reduces the self-interference mentioned in Section 3.1. As a simple case, consider that there are two very closely located devices that deploy the same AFH scheme and they collide if they use the same channel. Then, in the case of Fig. 2, the collision probability with RAFH is $[0.65\ \ 0.24\ \ 0.08\ \ 0.03] \cdot [0.65\ \ 0.24\ \ 0.08\ \ 0.03]^T = 0.49$ while that with the conventional AFH is 1.

The overall RAFH algorithm, which substantiates the idea of the constrained entropy maximisation approach, is given in Algorithm 1. In every interval of T, RAFH

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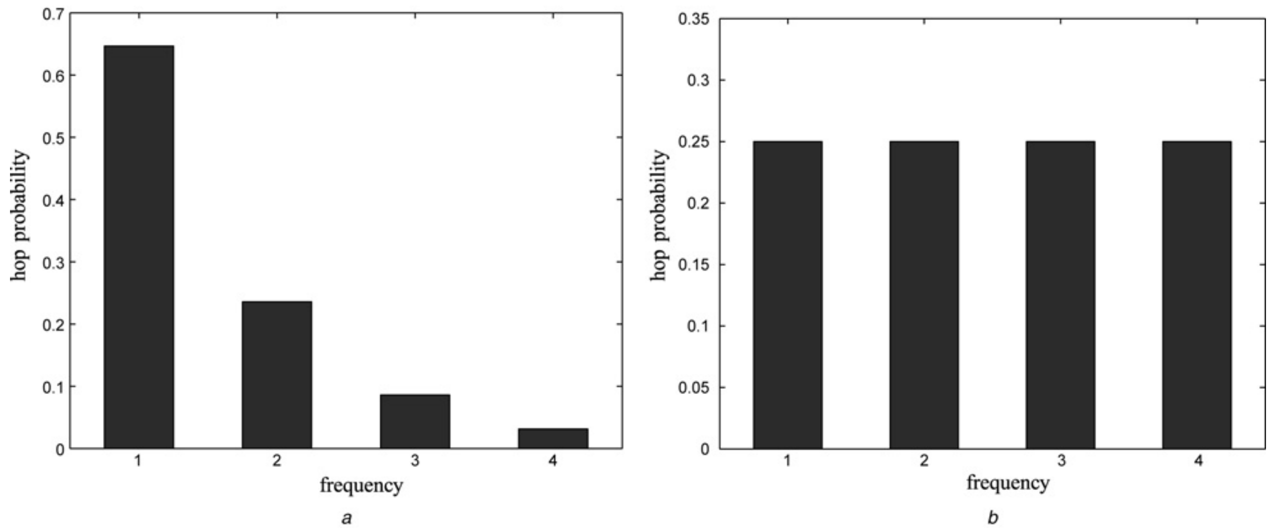

Figure 2 *Illustrative example on how the optimal solution* $\mathbf{p}^*$ *for (4) changes with respect to the PER threshold* ξ

a When $\xi = 0.15 < \sum_{i=1}^{M} a_i/M = 0.17$

b When $\xi = 0.20 > \sum_{i=1}^{M} a_i/M = 0.17$

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 $\boldsymbol{p}$ is triggered. When the PER constraint is feasible by the feasibility test in Line 21 of Algorithm 1, RAFH updates the hop probability $\boldsymbol{p}$ by maximising the entropy of $\boldsymbol{p}$ 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. (Since our future work will be to build a reliable telemetry system from a cross-layer approach, this alarm function will provide a useful way for coordination in cross-layer design.) At the same time, RAFH updates the hop probability set $\boldsymbol{p}$ so that only top K frequency channels are uniformly used, that is, $p_i = 1/K$ if $i \in S_K$ and $p_i = 0$ otherwise, where S_K is the set of top K frequencies with ascending order of PER.

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

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

In order to solve (4) efficiently, we rely on the convex optimisation theory [38]. First, we check the feasibility of (4). By inspection, we can easily notice that problem (4) is infeasible if $a_{\min} := \min a_i > \xi$. We will discuss this infeasible case later and tentatively assume that $a_{\min} := \min a_i \leq \xi$. The constrained convex optimisation problem (4) can be efficiently solved by using Lagrangian duality [38].

The basic idea of Lagrangian duality is to take account of the constraints in an convex optimisation problem by augmenting the objective function with a weighted sum of the constraints. The Lagrangian L associated with the problem (4) is given as follows

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

where λ and ν are called Lagrange multipliers. Now, we refer to the original optimisation 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 $\boldsymbol{p}$ as follows

$$\begin{aligned}g(\lambda, \nu) &= \inf_{\boldsymbol{p}} L(\boldsymbol{p}, \lambda, \nu)\\&= \inf_{\boldsymbol{p}}\left[\sum_{i=1}^{M} p_i \log p_i + \lambda(\boldsymbol{A}\boldsymbol{p} - \xi)\right.\\&\qquad\left. + \nu\left(\sum_{i=1}^{M} p_i - 1\right)\right]\end{aligned} \tag{6}$$

In (6), the dual function $g(\lambda, \nu)$ is concave because it is the

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Algorithm 1 Robust adaptive frequency hopping (RAFH)

// Initialisation
$\mathbf{p} \leftarrow [1/M \ldots 1/M]$
// PER estimation
Reset timer $t \leftarrow T$
$\mathbf{n}_t = (n_{1,t}, \ldots, n_{M,t}) \leftarrow \mathbf{0}$
$\mathbf{n}_e = (n_{1,e}, \ldots, n_{M,e}) \leftarrow \mathbf{0}$
while (True) **do**
  if current transmission uses frequency i **then**
    $n_{i,t} \leftarrow n_{i,t} + 1$
  end if
  if Transmission fails **then**
    $n_{i,e} \leftarrow n_{i,e} + 1$
  end if
end while
for $i = 1$ to M **do**
  $a_i = PER_i \leftarrow n_{i,e}/n_{i,t}$
end for
// update $\mathbf{p}$ if PER exceeds a given threshold η
if $PER = \sum_{i=1}^{M} n_{i,e} / \sum_{i}^{M} n_{i,t} > \eta$ **then**
  // feasibility test
  if $\min_i a_i \leq \xi$ **then**
    // Update $\mathbf{p}$
    $\mathbf{p} \leftarrow \arg\min_{\mathbf{p}} \sum_{i=1}^{M} p_i \log p_i$ such that $\sum_{i=1}^{M} a_i p_i \leq \xi$ and $\sum_{i=1}^{M} p_i = 1$
  else
    Alarm to the supervisory system
    $p_i = 1/K$ for the top K channels and $p_i = 0$ otherwise
  end if
end if

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

$$g(\lambda, \nu) \leq f^*$$

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

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

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 [38] and the optimal value for the dual problem (7) is equal to that of the primal problem (4). Consequently, convexity is the watershed for solving optimisation problems. In our formulation, since the overall problem can be easily shown to be convex, the duality approach can exactly solve the original problem. Hence, instead of solving the primal problem (4) directly, we can obtain the solution for (4) by solving the dual problem (7). Note that the dual problem (7) only have two variables, λ and ν, whereas the primal problem (4) has M variables. (Usually, M is much larger than two. for example, $M = 79$ for FHSS in the 2.4 GHz ISM band.) 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 $\boldsymbol{p}$. Hence, by plugging $\partial L/\partial p_i = \log p_i + 1 + a_i\lambda + \nu = 0$ into (5), we obtain

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

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

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as follows

$$\text{maximise} \; -\xi\lambda - \nu - e^{-\nu-1}\sum_{i=1}^{M} e^{-a_i\lambda} \tag{9}$$
$$\text{subject to } \lambda \geq 0$$

In order to further simplify the dual problem (9), we maximise 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 obtain

$$\text{maximise} \; -\xi\lambda - \log\left(\sum_{i=1}^{M} e^{-a_i\lambda}\right) \tag{11}$$
$$\text{subject to } \lambda \geq 0$$

After simple algebraic manipulation, (11) becomes

$$\text{minimise } h(\lambda) \equiv \sum_{i=1}^{M} e^{(\xi - a_i)\lambda} \tag{12}$$
$$\text{subject to } \lambda \geq 0$$

In the meantime, the necessary optimality condition for $\boldsymbol{p}$ 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 maximisation problem of (4) can be solved once we solve (12). Since (12) is a convex optimisation problem with only one variable λ, it can be efficiently solved by a gradient method. The two possible cases for (12) are given in Fig. 3. Let λ^* denote the optimal value of λ for (12). Then, if $h(\lambda)$ is strictly increasing as in Fig. 3*a*, we have $\lambda^* = 0$. Otherwise, $h(\lambda)$ is strictly decreasing for $\lambda \leq \lambda^*$ and strictly increasing for $\lambda \geq \lambda^*$ as shown in Fig. 3*b*. 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 $\mathrm{d}h(0)/\mathrm{d}\lambda \geq 0$, which can be easily verified from Fig. 3 by inspection. From (12), $\mathrm{d}h(0)/\mathrm{d}\lambda = \sum_{i=1}^{M}(\xi - a_i)$. 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 $\boldsymbol{p} = [1/M \ldots 1/M]^T$ satisfies the constraint in (4), then it will be the optimal solution to (4) because the uniform distribution maximises entropy over all the distributions. In this case, the constraint in (4) will be inactive, that is, $\boldsymbol{Ap} < \xi$, which exactly corresponds to the obtained condition with the uniform distribution of $\boldsymbol{p}$. Furthermore, λ^* will be zero according to the Karush–Kuhn–Tucker (KKT) condition [38].

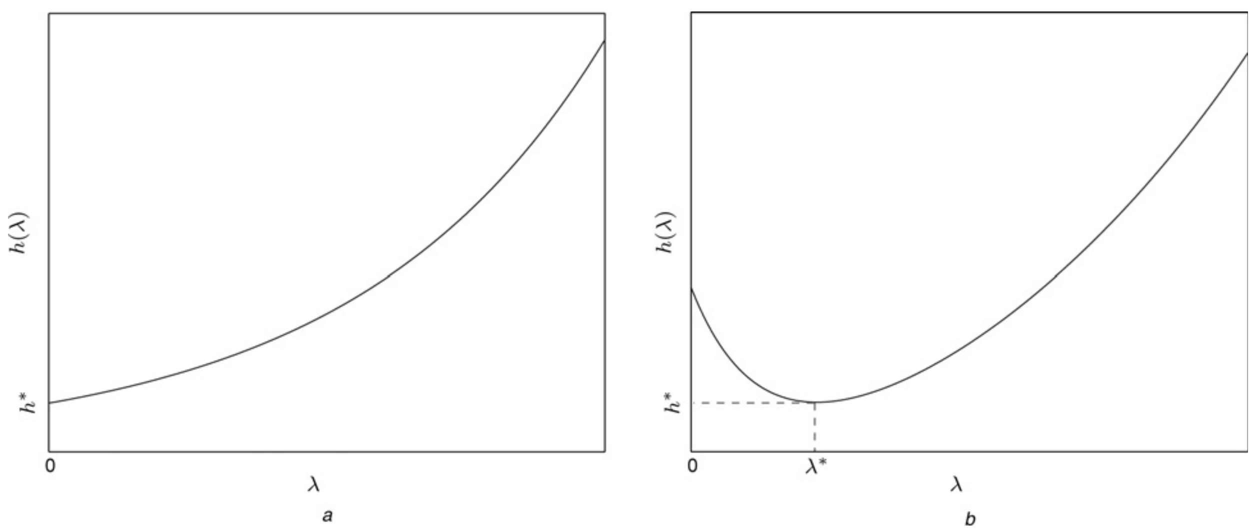

Figure 3 *Two cases for the optimal solution λ^* to the minimisation problem (12)*

a When $\lambda^* = 0$: $h(\lambda)$ is strictly increasing for $\lambda \geq 0$
b When $\lambda^* > 0$: $h(\lambda)$ is strictly decreasing for $\lambda \leq \lambda^*$ and strictly increasing for $\lambda \geq \lambda^*$

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Algorithm 2 A dual algorithm for solving the entropy maximisation 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: $\mathbf{p}$
$C \leftarrow \xi - A$; // $C = [c_1 \dots c_M]^T := [\xi - a_1 \dots \xi - a_M]^T$, M by 1 column vector
$\lambda \leftarrow 0$; // Initial λ
if $\sum_{i=1}^{M} c_i < 0$ **then**
  while $|\sum_{i=1}^{M} c_i e^{c_i \lambda}| > \epsilon$ **do**
    $\lambda \leftarrow \lambda - \alpha \sum_{i=1}^{M} c_i e^{c_i \lambda}$
  end while
end if
$\nu \leftarrow \log \sum_{i=1}^{M} e^{-a_i \lambda} - 1$
for $i = 1$ to M **do**
  $p_i \leftarrow e^{-(a_i \lambda + \nu + 1)}$
end for
Return $\mathbf{p}$

4 Simulation study

4.1 Simulation model

The simulation scenarios are designed to emphasise the dynamic pattern of interference. The FH sender hops around the 79 1-MHz frequency channels between 2.402 and 2.480 GHz. The duration time for each hop is fixed, which is considered as one time unit in the simulation. We consider the following two main sources of interference; basic FH interference either from co-existing 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 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. RAFH and the conventional AFH update the hop probability at every time interval of $T = 1000$ time units. Hereafter, we denote the conventional AFH as AFH in short (Table 1).

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

4.2 Simulation results

First, we show the average PER with respect to the number of FH interferers in Fig. 4. 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 interferer. 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. 4 is an average over ten simulation runs. Fig. 4 shows that RAFH outperforms basic FH and the conventional AFH with respect to the PER under a dynamic interference environment. As we can see from Fig. 4, 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 cannot 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 their 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 simulations for different values of T_s in

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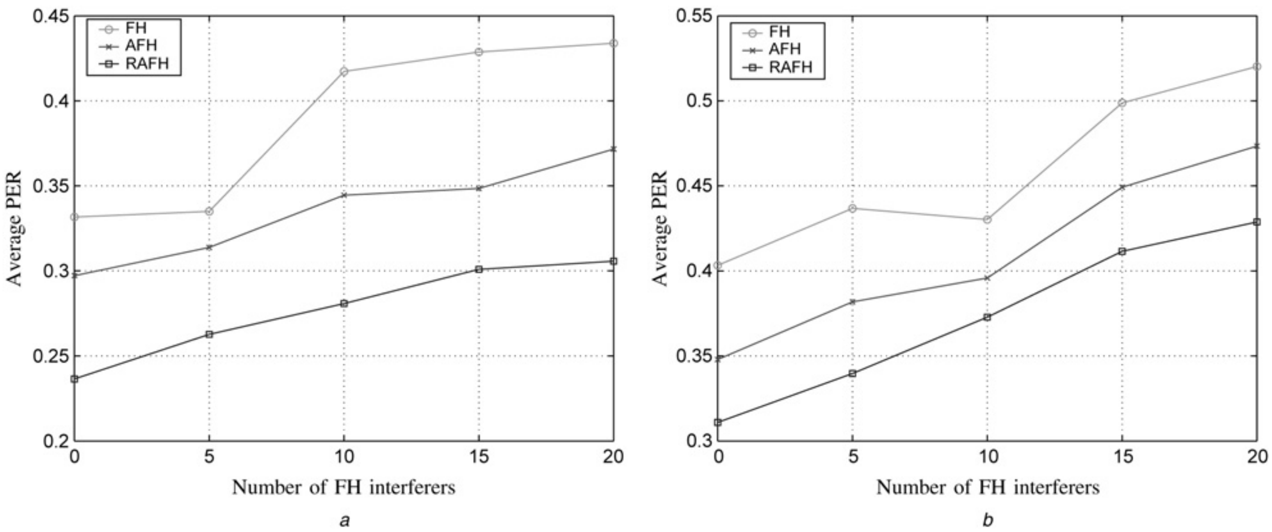

Figure 4 *Average PER vs number of FH interferers with random DS interferers*

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

Fig. 5, 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. 5*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. 5*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. 5*b*, RAFH reasonably keeps its PER around the threshold. In summary, the PER of AFH fluctuates with a period of the reset timer T_s while RAFH reasonably keeps its PER around the threshold. Even when the PER of AFH is similar with that of RAFH on average, the severe PER fluctuation of AFH will decrease the system reliability because the dropout rate (which is given in Section 3.2) is the probability that the PER exceeds a given level. Hence,

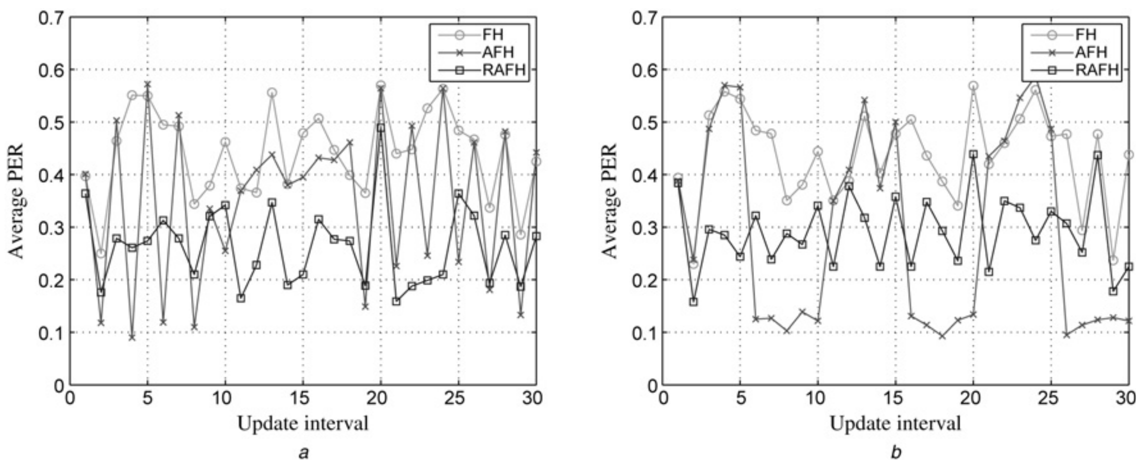

Figure 5 *Effect of the AFH reset timerT_s on PER fluctuation ($\gamma = 0.002$, $\mu = 0.001$, $\eta = \xi = 0.2$ and 10 FH interferers)*

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

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RAFH improves the reliability of WMTS by reducing the PER fluctuation.

Now, Fig. 6*a* shows the temporal behaviour of FH, AFH and RAFH whereas Fig. 6*b* shows the dynamic channel occupancy of DS interferers. Fig. 6*a* gives that the average PERs for FH, AFH and RAFH over the entire interval of $20T$ are 0.41, 0.37 and 0.28, respectively. In Fig. 6*b*, when there is no DS interferer, the channel value is set to $n_f - 0.5$ where n_f is the frequency channel number. Then, when a DS interferer arrives at the channel, the value is set to n_f. In Fig. 6*a*, there are abrupt increases in the PER at $t = 4T$ and $t = 7T$. The reason for these sudden changes in the PER can be found if we look into the dynamic activity of the DS interferers in Fig. 6*b*. Around $t = 3T$ (=3000) in Fig. 6*b*, both the second and the third channels are activated by new DS interferers, which abruptly increase the PER during $[3T, 4T]$. After this incident, the second channel for DS interference remains occupied except a short duration around $t = 5T$. Hence, frequencies in this channel are avoided in AFH or infrequently used in RAFH. During $t \in [4T, 6T]$, the third DS channel is not so much occupied by a DS interferer and hence frequencies in the third DS channel will be heavily used both in AFH and RAFH. However, just before $t = 6T$, a new DS interferer comes in the third channel, which makes the sudden increase in the PER at $t = 7T$ in Fig. 6*a*. In a similar manner, Fig. 7*a* shows the

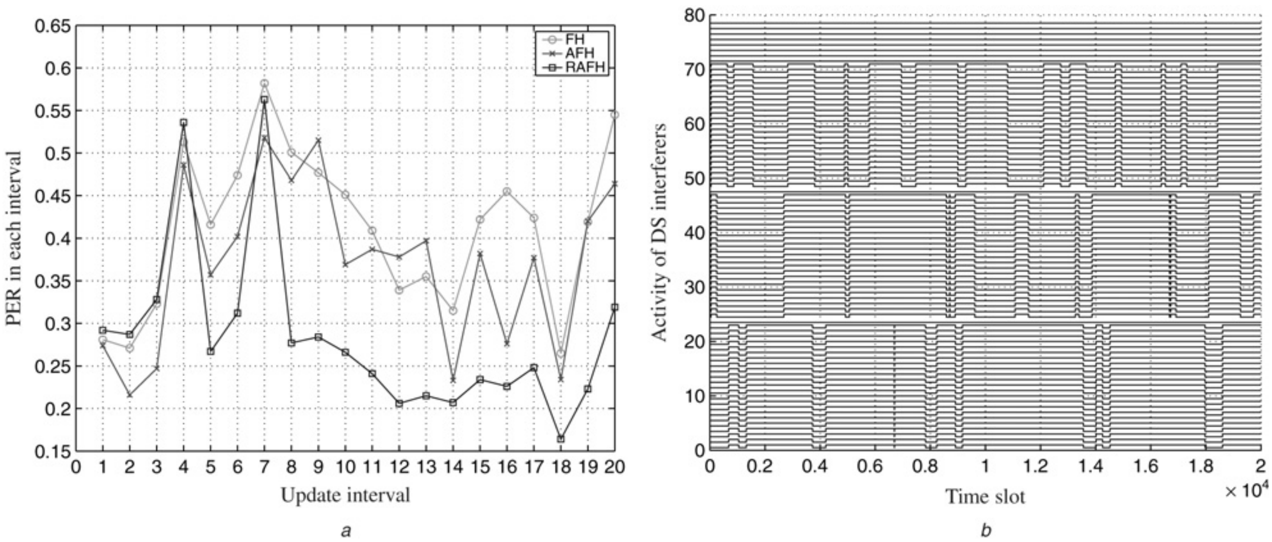

Figure 6 *Time traces PER and DS interferers when $\gamma = 0.002$, $\mu = 0.001$ and $\eta = \xi = 0.2$*

a PER in each update interval with five FH interferers and random DS interferers
b Activity of DS interferers in frequency channels

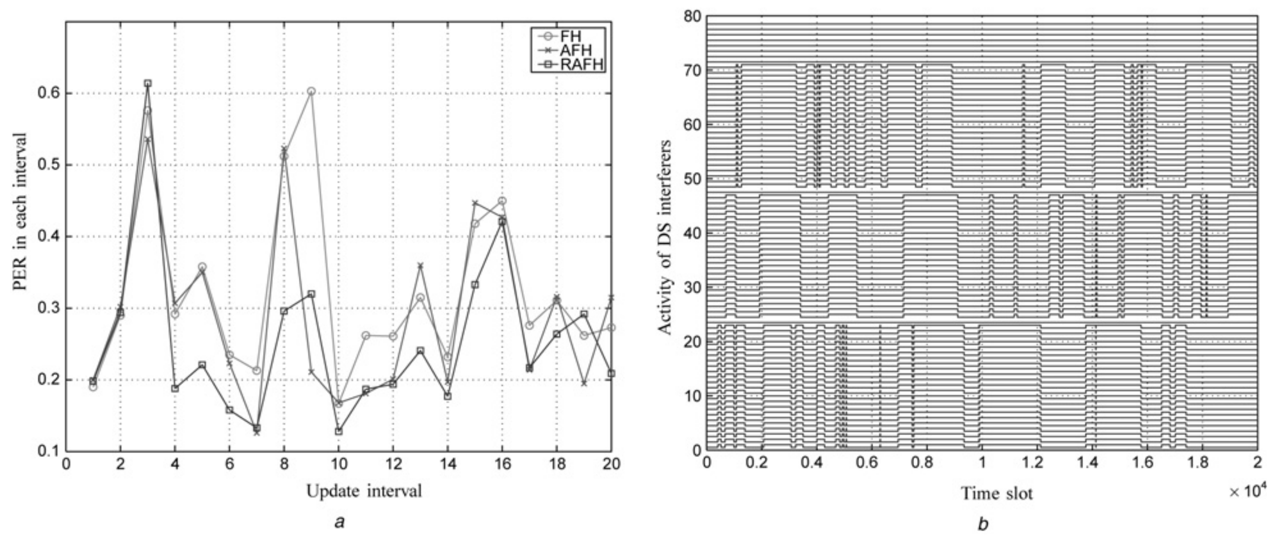

Figure 7 *Time traces of PER and DS interferers when $\gamma = 0.002$, $\mu = 0.002$ and $\eta = \xi = 0.3$*

a PER in each update interval with five FH interferers and random DS interferers
b Activity of DS interferers in frequency channels

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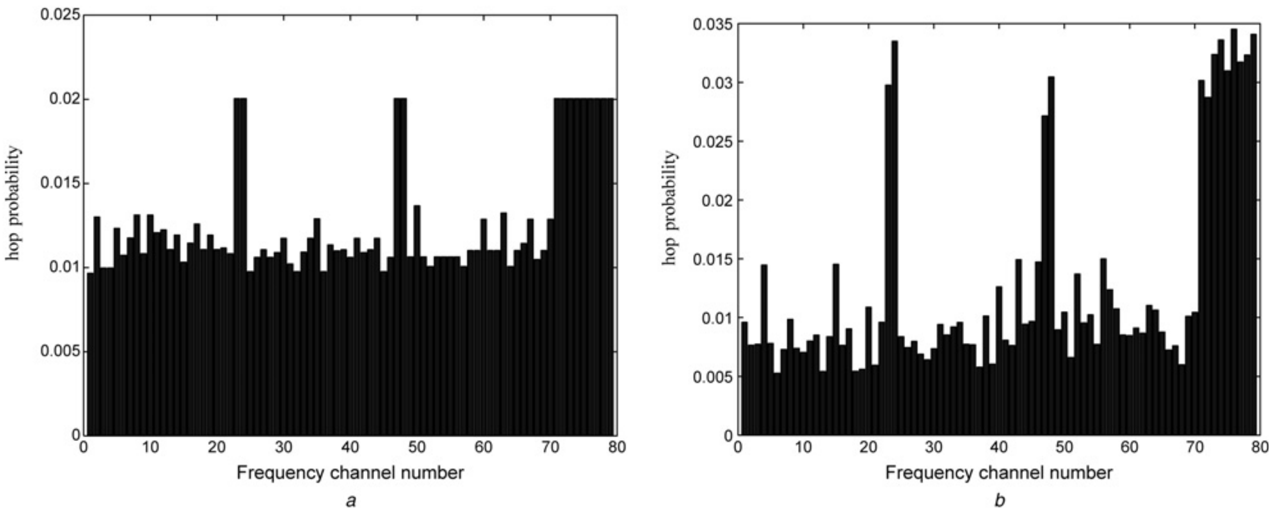

Figure 8 *Average hop probability of each frequency channel over 20T in the case of Fig. 7*
a Average hop probability of AFH
b Average hop probability of RAFH

temporal behaviour when $\gamma = 0.002$ and $\mu = 0.002$. Fig. 7*a* gives that the average PERs for FH, AFH and RAFH over the entire interval of $20T$ are 0.32, 0.29 and 0.25, respectively. In Fig. 7*b*, the average dwell time is $1/\mu = 500$, which is the half of that in Fig. 6*b*. From the figures, we can verify that the dwell time in Fig. 7*b* is smaller than that in Fig. 7*a*. Finally, Fig. 8 shows the average hop probability of each frequency channel over $20T$ (=20 000 time units) in the case of Fig. 7. From Fig. 8, we can know that RAFH uses the frequency channels unused by the DS interferers more often than AFH does.

5 Conclusion

In this paper, we have proposed an AFH scheme, entitled RAFH, for reliable wireless medical telemetry. RAFH maximises entropy of the hop probability set in order to fully exploit frequency diversity while satisfying a constraint on the total PER for estimated interference. The key novelty of RAFH over existing AFH is that RAFH assigns non-uniform hop probability by entropy maximisation in order to further enhance the communication performance. Note that the conventional AFH does not distinguish frequency channels as long as it exceeds a given threshold. Our simulation study has shown that RAFH outperforms basic FH and the conventional AFH with respect to the PER.

Our future work will involve building a highly reliable supervisory system for wireless medical networks on top of a RAFH-enabled physical layer. In fact, we are currently working for the Medical Device 'Plug-and-Play' Interoperability (MDPnP) Program [39] under collaboration with Massachusetts General Hospital. We are implementing a testbed for wireless medical networks, of which the physical layer is being built by GNU Radio [40], an open-source software defined radio technology. We expect that RAFH will be an efficient building block for our testbed to improve the reliability of the overall system.

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