FIREMAN: Foraging-Inspired Radio-Communication Energy Management for Green Multi-Radio Networks

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Abstract

The tremendously rapid evolution of wireless networks into the next generation heterogeneous broadband and mobile networks has necessitated the emergence of the multi-radio, wireless infrastructure. These wireless infrastructural technologies have been designed in such a manner as to enable them to be self-organised, self-configured, reliable and robust, with a capacity to sustain high traffic volumes and long "online" time. However, the desired networking and complex features have resulted in unnecessary network energy consumption, impacting negatively on the economy, environment and the ICT markets. In order to reduce the potential energy consumption in these networks, this chapter proposes a novel energy management scheme based on behavioural ecology. Inspired by the applied foraging theory, whereby a solitary forager in a random ecosystem makes optimal decisions that maximises its energy (nutrients) consumption, survival probability and lifetime, a Foraging-Inspired Radio-Communication Energy Management (FIREMAN) method has been developed. The FIREMAN method, consisting of optimal transmission energy allocation and energy saving efforts in multi-radio networks, has as its aim, the achievement of both optimal network energy consumption and lifetime. To attain a scalable solution, the FIREMAN method has been coordinated by a radio resource allocation protocol module built on the link layer of the networking protocol stack. The efficacy of the new method has been extensively validated through computer simulations of the energy and throughput performance. Future research directions linked to this contribution have also been furnished in this chapter.

Index terms

Autonomous foraging radio resource allocation (AFRRA) protocol; autonomous foraging radio resource allocation message (AFRRAM); energy management; FIREMAN; foraging-inspired; green multi-radio networks.

1. Introduction

In the past decade, the remarkably rapid evolution of wireless networks into the regime of the next generation heterogeneous broadband and mobile networks has triggered the emergence of multi-radio wireless infrastructures. Infrastructures of these types have been expected to integrate the future internet of people, technologies, content, and clouds into a common digital information society [1]. As a result, the move will eventually witness a harmonious co-existence of many wireless technologies in the same constrained radio resource environment in order to provide ubiquitous and seamless broadband services. To achieve this goal, the multi-radio networking technologies have to be designed in such a way as to ensure that they are self-organised, self-configured, reliable and robust with a capacity to sustain high traffic volumes and long “online” time [2].

Such complex functional and structural features stemming from the multi-radio networks will however, essentially cause unnecessary energy consumption in future networks [1]. Thus, it follows that the need to reduce the energy consumption in ICT industries becomes relevant in order to mitigate the adverse impacts of energy consumption on the economy, environment and ICT markets. To address this challenge, many studies have proposed several green strategies for wireless networking technologies and protocols [3]. For example, green strategies have been recently exploited to design energy-efficient residential gateways [4]. The gateways employ appropriate home networking interfaces and service logic to allow home owners to perform personalised, pervasive programming of the energy consumption of home devices such as electrical, communication and audiovisual equipment. The green networking research has also been considered, in order to address issues of autonomous link rate adaptation, interface proxying, energy awareness infrastructures and applications [3].

In a bid to contribute to the autonomy of energy-efficient architectures capable of supporting green heterogeneous wireless infrastructures and applications, this chapter proposes a novel energy management solution known as the Foraging-Inspired Radio-Communication Energy Management (FIREMAN) method. The FIREMAN method integrates the optimal transmission energy allocation with the energy saving efforts in multi-radio networks, so as to ensure a substantial energy consumption reduction in a random wireless ecosystem [5]. The main concept has been coined from the field of behavioural ecology, or foraging theory, in which a solitary forager in an ecosystem makes optimal decisions that maximise its rate of energy gain, thereby improving its survival probability and lifetime in a random environment [6]. Using this bio-inspired methodology, a solitary forager represents a foraging-inspired radio energy (FIRE) resource manager while the so called nutrients or prey mimic the radio communication energy resources that the radio interfaces need in order to exchange packets in a wireless link. The FIREMAN method involves the development of a prey model algorithm whereby the radio communication energy resources (energy link costs) are encountered randomly by the radio interfaces since the wireless links are stochastic in nature. In this manner, the algorithm maximises an energy-aware throughput (EAT) or communication profitability experienced in every link. The profitability is described by a set of feasible foraging behaviours consisting of optimising resource preference rates and allocation times which are capable of improving the energy consumption [7].

In order to minimise the multi-radio function complexities, the FIREMAN method is coordinated by an autonomous foraging radio resource allocation (AFRRA) protocol module built from an energy-aware multi-radio unification protocol (MUP) [8]. This module virtualises functions of multiple MACs and PHYs layers so that the application layers can only visualise the homogenous single radio networks rather than the complex heterogeneous wireless platforms. The performance of the developed FIRE manager has been extensively validated through computer simulations. This chapter has also provided future plans for prototype development suited for future networks. To our best knowledge, this work can be viewed as an early contribution towards the application of the foraging theory of nutrients optimisation to the field of green wireless networking research.

The remainder of this chapter is organised as follows: Related work in the field of radio energy management is discussed in Section 2. An autonomous foraging radio resource allocation (AFRRA) protocol will be presented in Section 3. In Section 4, the FIREMAN problem is formulated and a corresponding FIREMAN algorithm developed in Section 5. Section 6 provides the throughput and energy efficiency performance evaluation. Future research directions and conclusions regarding the FIREMAN method are presented in Sections 7 and 8, respectively.

2. Related work

The development of the FIREMAN method has been prompted by a number of experimental results stemming from measurements of the energy consumption behaviours in real Wi-Fi networks [9, 10]. In Gomez et al., [9], the actual impact between the traffic and power consumption for a typical wireless LAN (the IEEE 802.11b/g) access point (AP) was measured experimentally. The experimental results showed a significant impact of different traffic sizes on the power consumption pattern of the wireless devices, both at the interface level, with respect to the power expenditure for transmission and reception, and at the device level, with respect to the energy spent for processing the application traffic. In Carvalho et al., [10], an investigative study was conducted of the energy consumption of IEEE 802.11 cards when nodes were in contention for channel access under saturation conditions. In such scenarios, the study found that the radio's transmit mode had marginal impact on the overall energy consumption, while other modes (receive and idle) were responsible for most of the energy consumption. It was also noted that the energy link cost to transmit useful data increased almost linearly with the network size. Transmitting large payloads was more energy efficient under saturated conditions than small payloads.

The exploitation of the multi-channel MAC layer to provide an energy and spectrum efficient throughput had stimulated a flurry of research activities in power saving MAC protocols and algorithms [8],[12]-[14],[20]. Manweiler and Choudhury [11] proposed the SleepWell energy saving mechanism that achieved energy efficiency by evading the network contention in Wi-Fi networks. Different access points (APs) adjusted their activity cycles to minimally overlap with others and consequently to regulate the sleeping window of their clients in such a way that different APs were active or inactive during non-overlapping time windows. The SleepWell was implemented on a test-bed platform of eight laptops and Android phones. An evaluative study over a wide variety of scenarios and traffic patterns (YouTube, Pandora, FTP, Internet radio and mixed) showed a significant energy gain with a practically negligible loss of performance. The SleepWell enforced the energy efficiency through scheduling the activity cycles of APs during non-overlapping time windows to evade network contention, while the proposed FIREMAN method achieves energy-efficiency by enforcing the non foraging interface cards (NFICs) to go to the "doze mode", while the low power foraging interface card (FIC) indicates traffic belonging to the target receivers.

Anastasi et al., [12] presented an analytical model of a power-saving mode (PSM) aimed at reducing the energy consumption caused by the networking activities in IEEE 802.11 standard technologies. According to the IEEE 802.11 PSM algorithm, a mobile device is left in the active mode only for the time necessary to exchange data; it is turned to the sleep mode as soon as it becomes idle. In connecting to the infrastructure 802.11 WLAN or the Wi-Fi hotspot, the PSM algorithm was achieved by exploiting the role of the AP whereby each client station inside the hotspot informed the AP whether it utilised the PSM algorithm or not. As the AP relayed every frame from or to any client station, it buffered frames addressed to the client stations operating in the PSM while they were sleeping. Once during every beacon interval, usually (100 msec), the AP broadcast a beacon frame containing the Traffic Indication Map (TIM). The TIM indicated identifications of PSM stations whose application frames were buffered at the AP. The PSM stations were then synchronised with the AP and woken up to receive beacons. If these PSM stations were indicated in the TIM, they could download the application frames. Even though the PSM reduced the sensing or contention time, the TIM window was made static and only the energy consumption in the transmit mode was taken into account. Thus, Moshe et al., [13] extended this energy saving scheme to another method known as the LESS-MAC where the TIM window was made dynamic with respect to different payload sizes. Through simulations, the LESS-MAC was shown to save energy in the idle mode with minimal additional functionalities as in [12]. Moreover, the dynamic TIM window contributed a greater energy-saving in the transmit and receive modes. The FIREMAN algorithm autonomously adapts the energy link costs in a random wireless environment such that the per link energy aware throughput (EAT) is maximised.

Recently, the IEEE 802.11 PSM method has been extended by [14] to perform a TDMA based energy-efficient cognitive radio MAC (ECR-MAC) protocol. In this protocol, ad hoc nodes were allowed to dynamically negotiate multi-channels such that multiple radio communications could take place in the same region simultaneously, each in a different channel. In this way, the licensed primary users (PUs) could co-exist with non licensed users in an interference-free and ad hoc based multi-channel cognitive radio environment. To achieve the goal of reducing the idle time, the protocol divided time into fixed-time intervals using beacons and had a small window at the start of each interval to indicate the application traffic and negotiate channels. This protocol is complementary to the FIREMAN method except that the idle time and the energy link costs are minimised by the FIREMAN in order to realise a better energy-efficiency.

To express this concisely, these studies have focused on single radio based power saving mechanisms and not on the multi-radio wireless networks. The FIREMAN method, on the other hand, seeks to address the energy-efficient issues in multi-radio wireless networks wherein a very large percentage of the energy consumption arises. In Wang et al.,'s research study, [5], an opportunistic spectrum access and adaptive power management under the setting of multi-radio nodes and multi-channel wireless LANs was proposed. This power-saving multi-channel MAC (PSM-MMAC) protocol aimed at reducing the collision probability and the waiting time in the 'awake' state of a node under the distributed coordination function (DCF) mode [12],[24]. The protocol allowed for the estimation of the number of active links; selection of appropriate channels, radios and power states (i.e., awake or doze state), given the link estimates, queue lengths and channel conditions as well as the optimisation of the medium access probability in the p-persistent CSMA used in the data exchange. The simulation and analytical results showed an improved throughput, delay and energy efficient performance. However, several drawbacks associated with the PSM-MMAC were found: the default radio interface consumed a substantial amount of energy when estimating the number of active links and communicating the default channel to the rest of a dense network; there was no guarantee that the default radio interface was operating in low power modes during the ATIM window; the protocol considered the energy saving in the transmit mode only and not in the receive mode; and the PSM-MMAC did not provide a transmission energy control strategy; instead, all awake radios exchanged application frames using high transmission power levels. In contrast, the FIREMAN algorithm utilises the AFRRA protocol to perform the channel negotiation and traffic indication with the neighbouring nodes during the traffic and radio resource allocation window when the link is in both transmit and receive modes. The default radio interface (FIC) is enforced to operate in a low power mode to exchange control packets only while other radios use power-controlled levels to exchange the application traffic.

The implementation of the FIREMAN method is closely related to the one proposed by Lyberopoulos et al., [15] in which the authors presented an energy-efficient multi-radio platform. In this case, an examination of the efficient interfaces between the multiple heterogeneous radios and one or more processors on a single sensor node for energy-efficiency was performed. The authors focused on the effect of the application level parameters such as packet payload sizes and the packet transmission period on the energy consumption of CSMA protocols having multiple transmission attempts compatible with 802.15.4 and 802.11 MAC layer specifications. However, unlike the FIREMAN approach, the proposed platform did not suggest a unified layer to conceal the complex functions of the multiple radio interfaces and MACs from the upper layers.

To conceal this complexity, studies [1], [8], [16,17] proposed an autonomous transmission energy adaptation for multi-radio multi-channel wireless mesh networks. The transmission energy was dynamically adapted asynchronously or synchronously by each radio interface. The interfaces were coordinated by a power selection multi-radio multi-channel unification protocol (PMMUP) [8]. The transmission energy adaptations were based on the locally residing energy in a node, the amount of local queue load, the quality of the links and the interference conditions in the wireless medium [18, 19]. The authors divided the wireless mesh network (WMN) into a set of orthogonal unified channel graphs (UCGs) whereby each radio interface of each node was tuned to a unique graph. The PMMUP first set initial unification variables such as energy reserves and channel states from other UCGs; radio interfaces then predicted channel states of the wireless medium; the PMMUP updated the unification variables and finally, radio interfaces computed optimal transmission energy levels based on the predicted states [17]. However, effects of queue and link instability on the link-level energy consumption were not discussed by the PMMUP method.

In response to this gap, Olwal et al., [20, 21] modelled the inter-channel and co-channel interference, energy consumption at the queues, and the network connectivity problems as a joint queue-perturbation and weakly-coupled (SPWC) systems. A Markov chain model was developed to describe the steady state probability distribution behaviour of the queue energy and buffer state variations in multi-radio nodes. The impact of such queue perturbations on the transmission probability using some transmission energy values was analysed. The simulation results indicated that the proposed power control method converged at the steady state. Although the SPWC system was energy-aware, it was computationally complex and did not address the dynamic channel negotiations jointly with the energy-efficiency. Consequently, the proposed FIREMAN method has been developed. It simplifies the architectural and functional designs by exploiting the benefits of the AFRRA protocol, of searching for and optimising the locally available energy resources in a random wireless environment.

3. AFRRA protocol

The autonomous foraging radio resource allocation (AFRRA) protocol is an extension of the virtual MAC developed in [1], [16]. The AFRRA is a software module that controls functions of the foraging-radio interface cards (FICs) and the non foraging-radio interface cards (NFICs) in a highly random wireless ecosystem. The AFRRA protocol dynamically adapts the radio communication energy, channel negotiations and the energy saving mechanisms to achieve a foraging energy-efficient (FEE) network. The protocol assumes that every radio interface card in the “awake” state consumes a significant amount of the energy resource and that when in the doze state it consumes a very low energy resource. In the awake state, an interface may be in one of the three different modes: the transmit, receive and idle or sense modes [5].

3.1 Bio-inspired MAC firmware architecture

Consider a bio-inspired MAC firmware architecture shown in Figure 1, having an autonomous foraging resource allocation message (AFRRAM) window during which the channel negotiation or contention (in Phase 1) and the energy link cost estimation (in Phase 2) are performed and information are stored in the AFRRAM table. The first phase aims to form a link layer connection of nodes. When a node has data packets destined for another node or AFRRA, it may transmit an AFRRAM or, as it is conventionally known, an Ad hoc Traffic Indication Message (ATIM) via the awake default FIC to the intended receiver. The default FIC listens on the foraging frequency channel (FFC) during the AFRRAM window (meant for exchanging control messages only). Upon receiving an AFRRAM, the intended receiver FIC will reply with an AFRRAM-ACK message before data download commences. The transmission or retransmission of the AFRRAM follows the normal DCF access procedure [24].

In the second phase, the optimal link resources consisting of the energy costs and the frequency channels using the FIREMAN algorithm are determined. Following the end of the current AFRRAM window, any node, having neither sent an AFRRAM nor having received an AFRRAM via its FIC containing its own address, the initial frequency channel and power settings in the awake state during the AFRRAM window will enter the doze state. Any node which has sent an AFRRAM or received an AFRRAM containing its own address during the AFRRAM window will remain in the awake state until the end of the next AFRRAM window.

The third phase covers the exchange of the application data packets. These nodes in the awake state transmit/receive the application data packets and acknowledgements using the awakened NFICs. At the end of the beacon interval, all NFICs switch to the doze mode until the next packet arrivals.

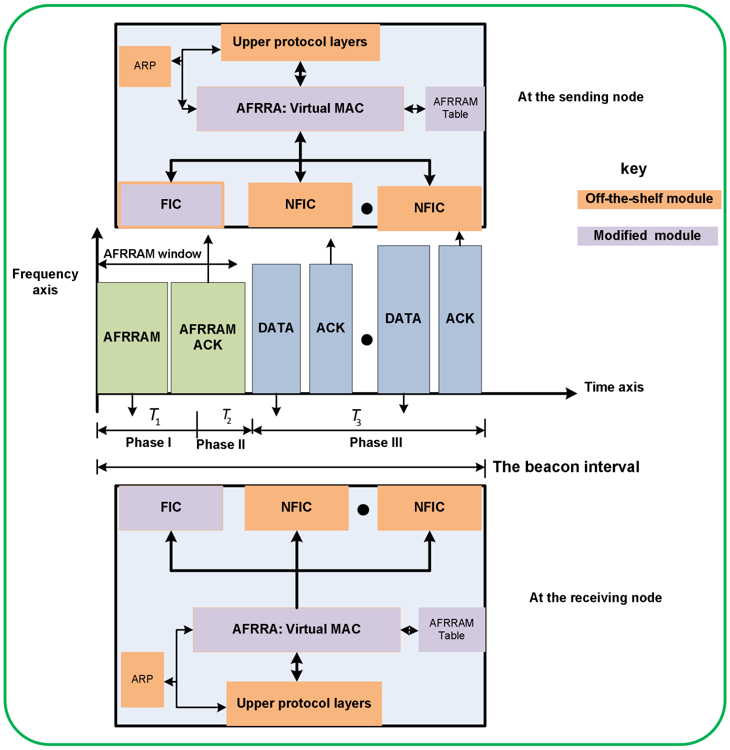


Figure 1: The proposed Bio-inspired MAC firmware architecture

3.2 The FIREMAN protocol

Figure 2 illustrates the bio-inspired radio resource (channel and energy link costs) allocation scheme in a random environment. Initially, at least one FIC, say a0 of node A, is awake at the default to estimate the energy link costs and allocate the frequency channels to the link. At the sending AFRRA, when this AFRRA has packets destined for another AFRRA in the network, it wakes up a default FIC and tunes the rest of the interfaces to the doze mode. The awakened FIC selects an initial random frequency channel using a low power mode, c0, as a default FFC from a pool of channels and an initial lowest possible power setting, p0, from a pool of the off-the-shelf power levels. The sending FIC advertises, to all its neighbours listening on all channels via their FICs: the AFRRAM consisting of the selected FFC, the selected power setting, the residual energy in the awake state and the MAC address of the intended receiving AFRRA. If received correctly, the receiving FICs reply with AFRRAM-ACK indicating to the sending FIC that they have received the sent AFRRAM containing their own address, the power setting and the sender's residual energy. If this does not occur, the link is either busy or the selected power setting cannot reach the intended receiver. If the link is busy, the sending FIC switches to the doze mode and re-advertises after a random back-off period of time. If the power setting is too low, then the AFRRAM is re-sent with a power setting level which is incrementally higher than the previous level. It should be noted that during the re-advertisements, different commodity power settings are selected, while the FFC and the address of the intended AFRRA are kept the same. Incrementing the transmission mode power settings increases the chances of reaching the intended receiver on subsequent re-transmissions. If a particular FFC has been grabbed, no other neighbouring link which hears that particular FFC should grab the reserved FFC for the transmission of its AFRRAM until the next AFRRAM window, thereby avoiding collisions amongst neighbouring transmitters. In Phase II of the proposed MAC firmware architecture and based on the successfully exchanged AFRRAM, the first task of each sending-receiving FIC pair or link is to find a set of power settings and thus, the estimate of the energy link costs. The second task that they have is to find a clumped patch of the frequency channel available for occupation in the network. The optimal resource type is free to be chosen, from a set of discrete power levels and the frequency channel cluster, from the unused spectrum in the available ISM bands.

At the intended receiving AFRRA, the FIC listens omni-directionally to receive FFCs, power settings, the residual energy from all possible sending AFRRAs in the awake state. In the meantime, the NFICs at the intended receiver node are compelled to enter the doze mode by the AFRRA in order to save the energy. If the FIC can hear or detect or sense the frequency channels from the sending AFRRAs, this means that the said FIC is listening on that FFC, and that the FFC is temporarily reserved for a period of the AFRRAM window. No other listening, neighbouring links are able to grab it. The FIC at the intended receiver grabs a frequency channel it detects if, and only if, that frequency channel contains the least amount of energy link costs and its own MAC address; otherwise it rejects any other frequency channels heard from the neighbourhood. If the AFRRAM is successfully received, then the FIC of the intended receiver replies with the AFRRAM-ACK message to the sending AFRRA. It should be noted that all power settings (prey types) sent to the intended neighbours but not received (detected) implies that they cannot guarantee the neighbourhood connectivity. All frequency channels (patch types) heard by the neighbours which do not contain their own MAC addresses imply that such neighbours cannot pick them up as they are already occupied as FFCs. Thus, they are ignored. The intended neighbouring AFRRA using AFRRAM-ACK messages replies to every sending AFRRA through the corresponding FICs and FFCs only; meanwhile all NFICs are switched to the doze state.

At the link layer, the intended receiving AFRRA and the sending AFRRA pair estimates the energy link costs (prey type executions) for every “hello packet” successfully sent and received at different radiated power levels by the FICs. Based on the estimates of each energy link cost, the AFRRA link computes the energy-aware throughput (EAT) and the foraging energy efficiency (FEE) that varies randomly from one energy link cost to the other, depending on the channel conditions. The optimal energy link cost (computed from the electronic energy of the receiver and transmitter interfaces, and the link radiated power) that yields the highest profitability measured in terms of the EAT compared to the FEE functions is selected by the AFRRA.

Following the end of the current AFRRAM window, the AFRRA wakes the NFICs and switches them randomly to the corresponding non overlapping channels to exchange the application data with the optimally computed energy link costs.

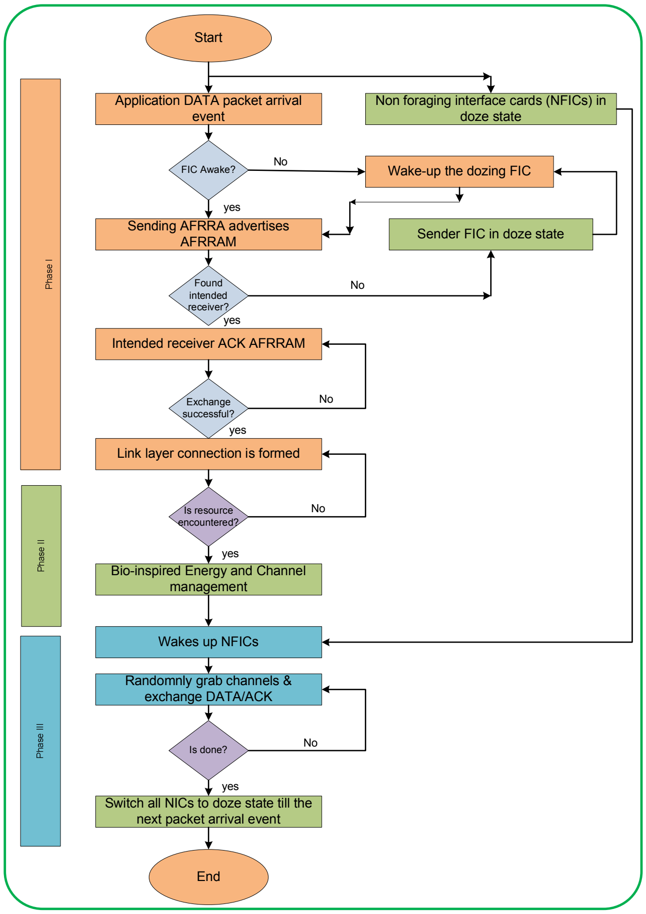


Figure 2: The proposed bio-inspired radio resource allocation scheme.

4. Problem formulation

The software AFRRA module represents the biological forager while the radio communication energy and channels it encounters are the tasks or resources it must optimally choose and determine for what period to allocate the links. In order to adopt the bio-inspired resource allocation algorithms, Stephens and Krebs [22] described two popular models. The first model was known as the prey model, which inspired the argument that the radio communication energy (i.e., prey) comes randomly in lumps or as individual quantities that have fixed resource allocation times (i.e., the processing-time constraints are such that $\tau_i^- = \tau_i^+ > 0$ for each resource type i). Thus, allocating optimal radio communication energy to a certain link follows the prey model algorithm. The AFRRA (i.e., forager) has only to decide whether to allocate the radio communication energy optimally or to ignore the allocation process and proceed to the next lump [7]. The second model was referred to as the patch model (i.e., a cluster of preys), which assumes that the AFRRA allocates the link to every encountered resource type (i.e., preference constraints $p_i^- = p_i^+ = 1$ for each resource type i), but each encountered resource is seen as a clumped patch of prey with decreasing marginal returns (e.g., due to the depletion of prey within the patch or set of prey). Since the channels in Wi-Fi networks are randomly encountered, allocating the link to an optimal channel follows the patch model algorithm whereby grabbing of one channel from the pool decreases the number of channels for other users within the same wireless environment. The AFRRA must decide on a length of time to process every patch based on a constant preference probability [6].

4.1 Objective function

Suppose that the AFRRA can complete allocating $n \in \{1,2,\ldots\}$ discrete types of distinct radio resources (i.e., energy link costs and channels) to the radio links. For a resource of type $i \in \{1,2,\ldots,n\}$, AFRRA allocates each radio link $p_i \in [0,1]$ fraction of the encountered energy and channel type i, and spends an average of $\tau_i \geq 0$ time allocating each selected type i. This implies that the complete radio resource allocation behaviour of the sending link is described by vectors $\vec{p} \triangleq [p_1, p_2, \ldots, p_n]^T$ and $\vec{\tau} \triangleq [\tau_1, \tau_2, \ldots, \tau_n]^T$ for all the resources. Constraints on the feasible behaviours are defined by constants $p_i^-, p_i^+ \in [0,1]$ and $\tau_i^-, \tau_i^+ \in \Re_{\geq 0}$ for each resource type $i \in \{1,2,\ldots,n\}$ so that the feasible set of behaviours becomes a *convex separable polyhedron* [23]:

$$\Gamma \triangleq \left\{ (\vec{p}, \vec{\tau}) \in [0,1]^n \times \Re_{\geq 0}^n : p_i^- \leq p_i \leq p_i^+,\ \tau_i^- \leq \tau_i \leq \tau_i^+,\ i \in \{1,2,\ldots,n\} \right\}. \tag{1}$$

The optimal behaviour of the AFRRA is to maximise the generic *advantage-to-disadvantage function* of each radio interface as is inspired by the foraging theory [23],

$$J(\vec{p},\vec{\tau}) \triangleq \frac{A(\vec{p},\vec{\tau})}{D(\vec{p},\vec{\tau})} \triangleq \frac{a+\sum_{i=1}^{n} p_i a_i(\tau_i)}{d+\sum_{i=1}^{n} p_i d_i(\tau_i)}, \tag{2}$$

where $a \in \Re$ and $d \in \Re$ are constants and $a_i : [\tau_i^-, \tau_i^+] \mapsto \Re$ and $d_i : [\tau_i^-, \tau_i^+] \mapsto \Re$ are functions of time τ_i associated with type $i \in \{1, 2, \ldots, n\}$. The type can be either any radio communication energy or any frequency channel. Then, the *advantage-to-disadvantage function* becomes the ratio of the expected link throughput to the expected radio communication energy consumed by that link. The function signifies the profitability of the AFRRA's decisions on energy link costs and channel allocations and is succinctly written as

$$J(\vec{p},\vec{\tau}) \triangleq \frac{\sum_{i=1}^{n} \lambda_i p_i^k \left\{ \left[w_i^k \log_2\left(1+SNR_i^k(\tau_i)\right) - O_i^{rate}(\tau_i) \right] \right\} - C^{search}}{\sum_{i=1}^{n} \lambda_i p_i^k \left[P_i^k(\tau_i) - O_i^{Pow}(\tau_i) \right]}, \tag{3}$$

whereby, for each resource type $i \in \{1, 2, \ldots, n\}$ and a corresponding resource allocation duration τ_i, several notations can be defined: λ_i is the rate of encounter with each resource type i, w_i^k is the channel bandwidth of resource type i associated with the radio interface k. The channel bandwidth is defined as, $w_i^k = 2\left(f_0^i - f_\ell^k\right)$, where $f_\ell^k = f_0^i - \frac{w}{2}$ is the lower frequency and f_0^ℓ is the middle frequency between the lower and the upper frequency bounds. The received signal to noise ratio from a resource type i is denoted as SNR_i^k, O_i^{rate} is the message overhead, O_i^{Pow} is the energy overhead and the P_i^k is the radio communication energy. The cost of searching for a certain resource type is denoted as, C^{search} and is assumed fixed. In an analogy with equation (2), the equation (3) is simplified as follows:

$a \triangleq -C^{search}$, $a_i(\tau_i) \triangleq \lambda_i\left[2\left(f_0^i - f_\ell^k\right)\log_2\left(1+SNR_i^k(\tau_i)\right) - O_i^{rate}(\tau_i)\right]$, $d \triangleq 0$, $d_i(\tau_i) \triangleq \lambda_i\left[P_i^k(\tau_i) - O_i^{Pow}(\tau_i)\right]$.

$b_i \triangleq \sum_{\substack{j=1 \\ j\neq i}}^{n} \lambda_j \left[2\left(f_0^i - f_\ell^k\right)\log_2\left(1+SNR_j^k\right) - O_j^{rate}\right]$, $e_i \triangleq \sum_{\substack{i=1 \\ j\neq i}}^{n} \lambda_i \left[P_i^k - O_i^{Pow}\right]$.

4.2 Radio resource decision variables

The radio resource decision variables are the radio communication energy and channels. In wireless commodity devices, the number of radio resource types, n, is free to be chosen as any reasonable number of discrete resource values available. The resource types and actual link variables have a distribution that resembles [7]:

$$i = ceil(n \times \exp(-R^k)), \tag{4}$$

where $k = 1, 2, \ldots, \kappa$ is the radio interface zone number, i is the resource type and $R^k \in [0, R_{\max}]$ is the resource variable belonging to the *k*th radio interface zone while the "ceil" is the standard ceiling function for converting non-integers to integers. The nonlinear relationship defines a large number of types for resource values within the range, thus providing a better accuracy near the real values. Equivalently, the resource values are derived by noting that $If\ y = b^x$, then $x = \log_b y$ so that,

$$R^k = -\log_e(i/n) \Rightarrow R^k = -\ln(i/n). \tag{5}$$

The resource allocation times for each resource type using the function is denoted as,

$$\tau_i = n + n \times \exp(-i). \tag{6}$$

The exponential characteristic of this function matches the distribution of processing times to the distribution of the resource types. Rates of encounter λ_i with different resource types are usually estimated in real time [7]. At any given instant, an estimate $\hat{\lambda}_i$ of the rate of encounter with type i is calculated as the number of times type i has been encountered by the AFRRA divided by the amount of time the AFRRA has spent searching for resources that it should allocate. Once the relationship between the radio resource value and type, the processing time function, τ_i and the objective function are determined, the FIREMAN algorithm executes an optimal radio communication energy management behaviour that maximises the objective function.

5. The FIREMAN algorithm

From the simplified objective function in (2), feasible solutions are obtained when the relevant assumptions are made. For example, the function d_i is constant and possibly zero; the constant $d \neq 0$; if $d_i \neq 0$, then it has the same sign as d; if d is positive, then a_i has a maximum, and if d is negative, then a_i has a minimum (i.e., function a_i / d has a maximum). The probability of allocating or processing each radio communication energy type is the decision variable for the AFRRA when applying the prey model to implement the FIREMAN algorithm. Thus, the AFRRA chooses p_i^k that maximises J defined in equation (3). Let J be rewritten as,

$$J(\vec{p},\vec{\tau}) = \frac{a + p_i^k \lambda_i a_i + b_i}{d + p_i^k \lambda_i d_i + e_i}, \tag{7}$$

where b_i is the summation of all terms in the numerator not involving the energy resource type i and e_i is a similar variable for the denominator. To obtain the value of p_i^k at which J is maximum, we differentiate J with respect to p_i^k,

$$\frac{\partial J}{\partial p_i^k} = \frac{\lambda_i a_i \left(d + p_i^k \lambda_i d_i + e_i\right) - \lambda_i d_i \left(a + p_i^k \lambda_i a_i + b_i\right)}{\left(d + p_i^k \lambda_i d_i + e_i\right)^2}$$

$$= \frac{\lambda_i a_i e_i - \lambda_i d_i b_i}{\left(d + p_i^k \lambda_i d_i + e_i\right)^2}. \tag{8}$$

By viewing equation (8), it is noted that if the numerator is negative, then J is maximised by choosing the lowest possible p_i^k. Alternatively, if the numerator is positive, then J is maximised by choosing the highest possible p_i^k. However, we know that, $0 \le p_i^k \le 1$. Thus, p_i^k that maximises J is either $p_i^k = 1$ or $p_i^k = 0$ for each $i \in \{1, 2, \ldots, n\}$. The decision depends directly on the sign of $a_i e_i - d_i b_i$. This type of decision is referred to as the *zero-one rule* which is summarised as,

$$\begin{array}{l} set\ p_i = 0\ \ if\ a_i / d_i < b_i / e_i \\ set\ p_i = 1\ \ if\ \ a_i / d_i > b_i / e_i \end{array}. \tag{9}$$

Here, a_i / d_i is the profitability that results from processing resource type i and b_i / e_i is the alternative profitability resulting from searching for and processing other resource types.

Using this rule, an AFRRA either processes energy of type $i \in \{1, 2, \ldots, n\}$ every time it encounters it or never processes it at all. The question is: which radio communication energy level the AFRRA should process and which level it should ignore? The answer for "which it should not" must account for the missed opportunity. That is, if it profits the AFRRA more when it allocates the energy of type i than that of searching for and allocating the energy of other types, then the AFRRA should process the energy of type i and ignore other types. Conversely, if more benefits are likely to derive through processing other energy types other than those of type i, then the AFRRA should ignore type i.

To process multiple types, the radio communication energy levels are first ranked or sorted according to their profitability such as that $a_1 / d_1 > a_2 / d_2 > \ldots > a_n / d_n$. If type j is included in the AFRRA's "resource allocation pool" (those types that the AFRRA will process, once encountered), then all types with profitability greater than that of type j will be included in this pool as well. After ranking the resource types by profitability, types are included in the pool iteratively, starting with the most profitable type (i.e., when $i=1$) until the following condition is attained:

$$\frac{\sum_{i=1}^{j}\lambda_i a_i}{\sum_{i=1}^{j}\lambda_i d_i} > \frac{a_{j+1}}{d_{j+1}}. \tag{10}$$

The highest j that satisfies the equation (10) is the least profitable resource type which is included in the pool. That is, if resource types in the environment are ranked according to profitability with $i=1$ being the most profitable, and if type $j+1$ is the least profitable type such that the AFRRA will benefit more from searching for and processing types with profitability higher than the profitability of $j+1$, then resource types 1 through j should be processed when encountered and all other resources should not. If the equation (10) does not hold for any j, then all resources should be processed when encountered. The most profitable type j is substituted into equation (5) as the optimal radio communication energy.

6. Performance evaluation

To evaluate the performance of the foraging-inspired radio communication energy management (FIREMAN) method, the above algorithm was validated using the MATLAB simulation tool. The tool has a computational capability to simulate realistic physical channel characteristics and radio link energy costs of a distributed small number of nodes. To assess the impact of the FIREMAN on the network topology, ten stationary wireless multi-radio nodes with a maximum transmission range of 500 m were uniformly placed in a 1000 m x 1000 m area. Each node had up to 4 radio interfaces with one interface acting as a default FIC for exchanging control messages and others operating as the NFICs for exchanging the application traffic. Following the proposed FIREMAN algorithm and AFRRA protocol, the interfaces were each tuned to non-overlapping UCGs of frequency spectrum available between 2.412 GHz and 2.484 GHz [24]. The orthogonal channel numbers 1, 6, 11 and 14 of channel-widths of 20 MHz each in the IEEE 802.11 b/g were considered [24]. Depending on the phases within a beacon time interval, certain radio interfaces were set to either doze or active states. Application packets arrived at each MAC and PHY layers' queue following a Poisson process [20]. In each arrival, the sender node sent an AFRRAM to the intended receiver during the AFRRAM window. For each arriving packet, time was divided into identical beacon intervals of typically 1 second. At the start of each beacon interval, all nodes stayed awake via their FICs for duration of an AFRRAM window. During the AFRRAM window, the FIC executed traffic indication, the FIREMAN algorithm, and the channel negotiation mechanism.

The radio communication energy in transmit and receive modes was evaluated from the FIREMAN algorithm. The radio communication energy in a link in the transmit mode was considered as the energy link cost. A link was said to be in the transmit state if the sending interface was transmitting packets (control or data) to a receiving interface connected to it on the same physical link. That is, the sum of the radio transmit, receive and the device-pair electronics' energy constitutes the transmit energy consumption of a link. The energy per link in the receive mode was the sum of the receive and device-pair electronic energy. A link was said to be in the receive, idle, or doze state, respectively, if any two devices were receiving or idle listening or dozing with respect to the neighbour transmissions in the direction of the same virtual link. The performance evaluation concerning the energy consumption after executing the FIREMAN algorithm was performed for a duration sufficiently long for the output statistics to stabilise (i.e., 60 s). Each datum point in the plots was the result of averaging four data points from four simulation runs, whereby each run represented a different randomly generated network topology of the same number of the nodes. The rest of the system performance was generated from parameters specified in Table 1.

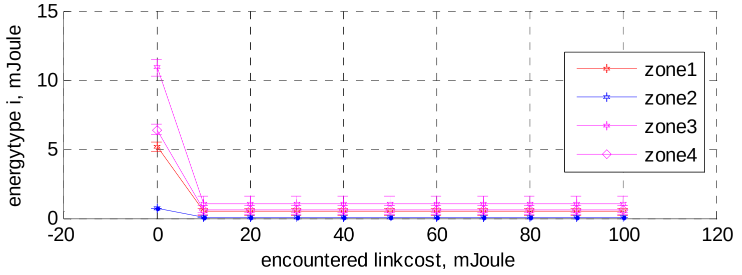
Table 1: Performance evaluation parameters

Parameter	Definition and description	Specification
Transmission rate	Basic interface rate for both the AFRRAM and DATA exchanges	2 Mbps
Payload length	Fixed, 456 of DATA, 16 of UDP, 40 of IP	512 bytes
Buffer length	Fixed	50 bytes
Beacon-interval	Fixed, AFRRAM window (T1+T2), DATA (T3) window T1: The channel negotiation window T2: The AFRRAM exchange window T3: The payload data exchange window T4: The doze mode window. Randomly chosen if the start of the next beacon or the traffic load delays by over 10 ms (about 1% of the beacon interval)	T1, max = 1 ms T2, max = 330 ms, depending on the AFRRAM traffic in the medium T3 = Variable, depending on the data traffic in the medium T1+T2+T3 = 1000 ms
Adjustment factor	Adjustable AFRRAM window	Varied from 1.2-1.5
Electronics (Tx & Rx)	Transmission and reception electronic energy consumption	50 micro-Joules/bit
No of active links	Active links per node Active links per network of 10 nodes	Varied from 2 to 4 Varied from 20 to 40
No of channels	Non interfering channels in the network (2412, 2437, 2462, 2484 MHz)	Varied from 1 to 4
No of interfaces per node	Total number of interfaces per node is at most the sum of incoming and outgoing active links per node	Varied from 2 to 4
Traffic load or the	Load injected to each link	Varied from 1 to 10 packets/sec/link

UDP test traffic		Constant bit rate (CBR)
MAC overhead	24 bytes of PLCP header (which is transmitted @ 1 Mbps) + 20 byte MAC frame header	48 bytes
DIFS	Distributed Inter Frame Space	50 micro Seconds
SIFS	Short Inter Frame Space	10 micro Seconds
Back- off slot time	Time taken in low transmission energy state when a collision is detected.	20 micro Seconds

In Figure 3, the average energy types and link costs distributions at the four radio interface zones are shown with a 95% level of confidence. As the encountered link cost increases, the energy types drop from some high values and become constant thereafter. Conversely, the increase in types causes the link cost to show an inverse response with the link costs. This is because, given the available transmission energy settings of a commodity Wi-Fi device, the exponential types distribution function provides an inverse relation with the energy settings. For example, at the third zone, 0 mJoules (type 11) to 100 mJoules (type 1) of the multi-radio IEEE 802.11b/g. Type 11 signifies the least energy cost consumed by the link, while Type 1 shows the highest energy cost consumed by the same link. The exponential type distribution function was chosen because of its ability to define a large number of energy types for energy link costs with small order of magnitudes (i.e., mJoules) as compatible with the most wireless LAN commercial devices. The exploitation of a large number of types gives the forager a set of alternative choices for making more accurate decisions in the foraging-inspired resource optimisations [7].

(a): radio energytypes



(b): energy linkcosts

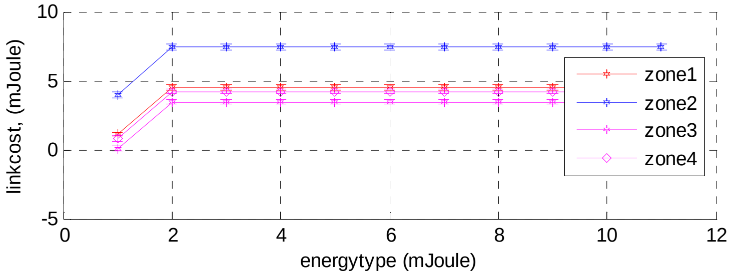


Figure 3: Average energy link cost types for multi-interface zones: (a) energy types and (b) energy link costs.

In Figure 4, the average performance of the FIREMAN method with a 95% confidence level, when applied to the radio communication energy allocation in multi-radio network, is depicted. Figure 4a illustrates the effect of the radio communication energy on the energy aware throughput (EAT) performance. The EAT performance mimics the foraging profitability function, where the biological forager increases its nutrient value (kCal) by spending its time searching for certain prey or nutrient types which can provide high nutrient contents. As the radio communication energy increases, the EAT drops linearly, rapidly, due to the increase in the energy cost of communicating packets in the network. The NFIC zones have higher profitability than the FIC zone as the energy cost increases, because the NFIC zones perform overhead free, data exchanges with the controlled radio communication energy, while the FIC zone exchanges overhead control messages. Specially, at 10 mJoules, the NFIC$_1$ zone provides 70% more throughput profitability than that of the FIC zone, on the average.

Figure 4b portrays the effect of the radio communication energy on the foraging energy efficient (FEE) performance. The FEE performance mimics the foraging loss function, where the biological forager decreases or wastes kCal by spending its time searching for certain prey or nutrient types which can only provide low nutrient contents. As the radio communication energy increases, the FEE charged increases linearly, rapidly, due to the increase in the cost of communicating packets in the network. The NFICs zones are more energy-efficient than the FIC zone, because the NFIC zones not only use the controlled energy levels but also stay awake only on demand (when there are application packets destined to a certain receiver). Otherwise all NFICs stay in the doze mode throughout the beacon interval. In contrast, the FIC zone stays awake to coordinate the exchange of control packets between the AFRRA pairs and only stays in the doze mode for short intervals when application data is being exchanged. Specifically, at 60 mJoules, the NFIC consumes 67% less energy than that of the FIC zone, on the average.

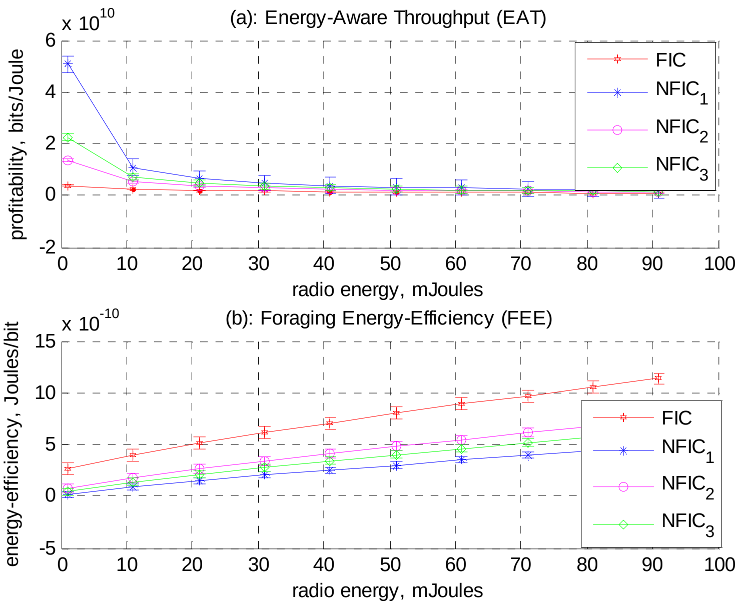


Figure 4: (a) Average energy-aware throughput and (b) average foraging energy-efficiency versus radio energy cost.

Figure 5 illustrates the impact of the traffic load offered to each link on the energy-aware throughput (EAT) performance and on the corresponding foraging energy efficiency (FEE) performance. Figure 5a suggests that more traffic loading onto the link leads to a better energy-aware throughput (EAT) performance per each link. The performance results agree with the theory that the offered load per link is directly proportional to the throughput in a lightly loaded network. The FIREMAN method was compared with the power-saving multi-channel medium access control (PSM-MMAC) protocol suggested in [5] and the singularly-perturbed weakly-coupled based power selection multi-radio unification protocol (SPWC-PMMUP) proposed in [20]. It has been found that the FIREMAN method for a three radio interface link outperforms the SPWC-PMMUP and PSM-MMAC methods tested under a similar number of the radio interfaces, on the average. Specifically, at 10 packets, on the average, the FIREMAN method records 20% and 60% more EAT performance than those of the SPWC-PMMUP and PSM-MMAC methods, respectively. The findings are attributed to the reason that the FIREMAN algorithm is capable of making optimal decisions in a random wireless environment. It forces the FIC to exchange the control messages, while the NFICs exchange the application data packets on separate radio links and non overlapping channels. In contrast, the PSM-MMAC protocol executes the RTS/CTS handshake at a full radiated energy when attempting to reduce the hidden terminal problems, at the expense of the increased message overheads. The SPWC-PMMUP method imposes some computational complexity when evaluating the queue perturbation and weak coupling coefficients. Increased computational time intervals leave less time available for the exchange of application data. Both the PSM-MMAC and SPWC-PMMUP methods assume static channel assignment irrespective of the channel qualities. Instead, the FIREMAN method has a quasi-static channel assignment whereby channels are assigned in every beacon intervals but which dynamically changes with respect to the energy link costs (the link with the least energy cost is assigned a channel).

In Figure 5b, a corresponding average foraging energy-efficiency (FEE) performance is shown whereby the FIREMAN method indicates the best FEE compared to the other conventional methods. Specifically, at 2 packets, on the average, the FIREMAN method has 35% and 42% better FEE performance than the SPWC-PMMUP and PSM-MMAC methods, respectively. The reason is that the FIREMAN method forces the control messages' intervals to be as short as possible to allow longer intervals for the application data exchanges and to reduce the idle time of the FICs. All the NFICs are switched off until the energy is allocated and the channel is negotiated to save significant amounts of energy. Nodes stay awake only on demand; otherwise they are switched off in the network. The FIREMAN method also ensures that soon after the data exchange and the current beacon interval have expired, all the radio interfaces are switched to doze mode until the next application packet arrives.

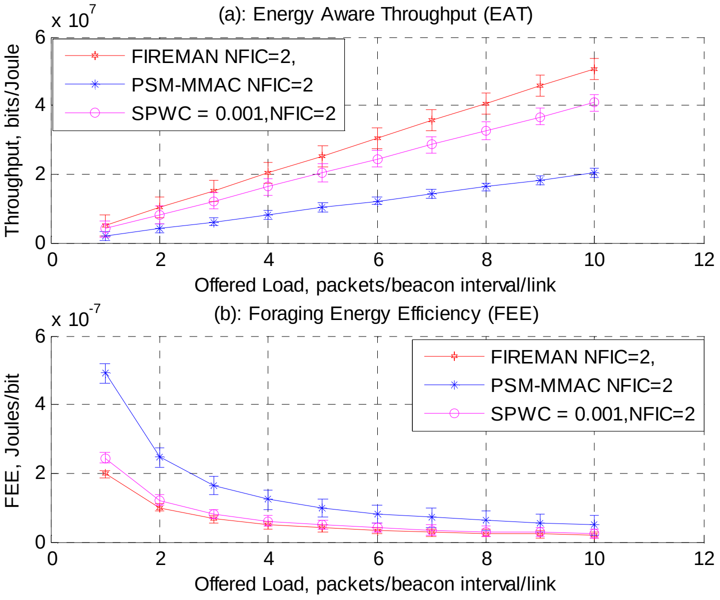


Figure 5: (a): EAT and (b): FEE versus Offered traffic load per beacon interval per link.

7. Future research directions

Future research involves the extension of the FIREMAN method to the implementation of joint dynamic energy and channel assignment in the wireless broadband networks. In such a design, the modified link layer firmware will be expected to execute the cross layer energy management for lifetime maximisation, while ensuring that the available frequency channels are dynamically assigned to the active communication links. These anticipated research studies will also involve the investigation of the energy and spectrum acquisition from a network environment by utilising foraging search techniques. The central notion will be to have both resource acquisition and optimal management integrated into a single foraging life-cycle, closely resembling the case of biological foragers who search for nutrients in a random environment. When said biological foragers encounter nutrients, they decide whether to consume or ignore these based on the perceived energy gain and lifetime maximisation.

8. Conclusion

The chapter has proposed a foraging-inspired radio communication energy management protocol (FIREMAN) for green multi-radio networks. The protocol and algorithm designs of the FIREMAN, as motivated by a random wireless environment, have been presented here. The computer simulations have been used to validate the designs and have shown better throughput and energy-efficiency performances than the conventional energy management methods. This result holds promise for the implementation of green heterogeneous wireless networks as discussed in section 7. The future work of this study involves the software development of the prototype for real-life performance tests. The test findings will be used to scale the application of the FIREMAN to large heterogeneous wireless networks.

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