The FIREMAN: Foraging-Inspired Energy Management in Multi-Radio Wi-Fi 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 paper proposes a novel energy management scheme based on behavioral ecology. Inspired by the applied foraging theory, whereby a solitary forager in a random ecosystem makes optimal decisions that maximizes 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 Wi-Fi networks, has as its aim, the achievement of both optimal network energy consumption and lifetime. The efficacy of the new method has been extensively validated through computer simulations of the energy and throughput performance.**

Keywords*—*Autonomous foraging radio resource allocation (AFRRA) protocol; autonomous foraging radio resource allocation message (AFRRAM); energy management; FIREMAN; foraging-inspired; Wi-Fi multi-radio networks.

I. 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 likely 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 personalized, 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 and energy-aware infrastructures [3].

In a bid to contribute to the autonomy of energy-efficient architectures capable of supporting green heterogeneous wireless infrastructures and applications, this paper 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 Wi-Fi 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 behavioral ecology, or foraging theory, in which a solitary forager in an ecosystem makes optimal decisions that maximize 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 maximizes 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]. The performance of the developed FIREMAN has been extensively validated through computer simulations. To our best knowledge, this work can be viewed as an early contribution towards the application of the foraging theory of nutrients optimization to the field of green wireless networking research.

The remainder of this paper is organized as follows: Related work in the field of radio energy management is discussed in Section II. In Sections III and IV the FIREMAN protocol and problem are formulated. A corresponding FIREMAN algorithm is developed in Section V. Section VI provides the throughput and energy efficiency performance. Conclusions and Future Research are given in Section VII.

II. RELATED WORK

The development of the FIREMAN method has been prompted by a number of experimental results stemming from measurements of the energy consumption behaviors in real Wi-Fi networks [9, 10]. In [9], the actual impact between the traffic and power consumption for a typical wireless LAN access point (AP) was measured experimentally. 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],[10]-[13],[17]. In [10], the SleepWell energy saving mechanism that achieved energy efficiency by evading the network contention was proposed. In this method, 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. Anastasi et al., [11] 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. Even though the PSM reduced the sensing or contention time, the traffic indication map (TIM) window was made static and only the energy consumption in the transmit mode was taken into account. Thus, [12] improved 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.

Recently, the IEEE 802.11 PSM method has been extended by [13] 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. This goal was achieved by reducing the idle time.

However, such 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 Wi-Fi networks wherein a very large percentage of the energy consumption arises. In [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 [11], [18]. 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. However, 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. In contrast, the FIREMAN algorithm utilizes the link layer protocol [8] to perform the channel negotiation and traffic indication with the neighboring 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 work in [14] 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. 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. Studies in [1], [8], [15] 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 [16]. In [17], the inter-channel, co-channel interference, and energy consumption at the queues were modeled as joint queue-perturbation and weakly-coupled (SPWC) systems. A Markov chain model was developed to describe the steady state probability distribution behavior 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 analyzed. Although the SPWC system was energy-aware, it was computationally complex and did not address the dynamic channel negotiations jointly with the energy-efficiency. This issue has been resolved by the FIREMAN method via an autonomous foraging radio resource allocation (AFRRA) protocol implemented at the link layer [1].

III. THE FIREMAN PROTOCOL

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 node, when the autonomous foraging radio resource allocator (AFRRA) has packets destined for another in the network, it wakes up a default foraging interface card (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 foraging frequency channel (FFC) from a pool of channels and an initial lowest possible power setting, p0, from a pool of the commodity power levels. The sending FIC advertises, to all its neighbours listening on all channels via their FICs: the allocator message called ‘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. 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. After successful exchanges of the AFRRAM messages, 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. This is done according to the proceeding formulated problem and algorithm.

IV. PROBLEM FORMULATION

Suppose that the *forager (*AFRRA*)* can complete allocating $n \in \{1,2,...\}$ discrete types of distinct radio resources (i.e., energy link costs and channels) to the radio links. For a resource of type $i \in \{1,2,\ldots,n\}$, it allocates each 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. The feasible set of behaviours becomes a convex separable polyhedron [6]:

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

The optimal behavior of the forager is to maximize the generic *advantage-to-disadvantage function* of each radio interface as is inspired by the foraging theory [6],

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

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 $i \in \{1, 2, \ldots, n\}$. If the type is either any radio communication energy or any frequency channel, then the (2) becomes the ratio of the expected throughput to the expected 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 (2), the expression (3) is simplified as follows:

$$a \triangleq -C^{search},$$

$$a_i(\tau_i) \triangleq \lambda_i\left[2\left(f_0^i - f_\ell^k\right)\log_2\left(1+SNR_i^k(\tau_i)\right) - O_i^{rate}(\tau_i)\right],$$

$$d \triangleq 0,\ d_i(\tau_i) \triangleq \lambda_i\left[P_i^k(\tau_i) - O_i^{Pow}(\tau_i)\right].$$

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

$$e_i \triangleq \sum_{\substack{i=1 \\ j\neq i}}^{n} \lambda_i\left[P_i^k - O_i^{Pow}\right]. \tag{4}$$

At any given instant in time, 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 communication energy management behavior that maximizes (3).

V. THE FIREMAN ALGORITHM

Based on (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). Thus, the AFRRA chooses p_i^k that maximises J defined in (3). Let J be rewritten as,

$$J(\vec{p},\vec{\tau}) = \frac{a + p_i^k\lambda_i a_i + b_i}{d + p_i^k\lambda_i d_i + e_i}, \tag{5}$$

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,

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

$$= \frac{\lambda_i a_i e_i - \lambda_i d_i b_i}{\left(d + p_i^k\lambda_i d_i + e_i\right)^2}. \tag{6}$$

By viewing equation (6), it is noted that if the numerator is negative, then J is maximized by choosing the lowest possible p_i^k. Alternatively, if the numerator is positive, then J is maximized by choosing the highest possible p_i^k. However, we know that, $0 \leq p_i^k \leq 1$. Thus, p_i^k that maximizes 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 summarized as,

$$\begin{array}{l} set\ p_i = 0\ if\ a_i / d_i < b_i / e_i \\ set\ p_i = 1\ if\ a_i / d_i > b_i / e_i \end{array}. \tag{7}$$

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.

In order to process multiple types, the 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:

$$\frac{\sum_{i=1}^{j}\lambda_i a_i}{\sum_{i=1}^{j}\lambda_i d_i} > \frac{a_{j+1}}{d_{j+1}}. \tag{8}$$

The highest j that satisfies the equation (8) is the least profitable resource type which is included in the pool.

VI. PERFORMANCE EVALUATION

To evaluate the performance of the foraging-inspired radio communication energy management (FIREMAN) method, the above algorithm was validated using computer simulations of ten stationary wireless multi-radio nodes. 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, the interfaces were each tuned to non-overlapping frequency spectrum available between 2.412 GHz and 2.484 GHz [18]. 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 [18]. 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 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 neighbor 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 stabilize (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.

In Fig. 1, 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 optimizations [7].

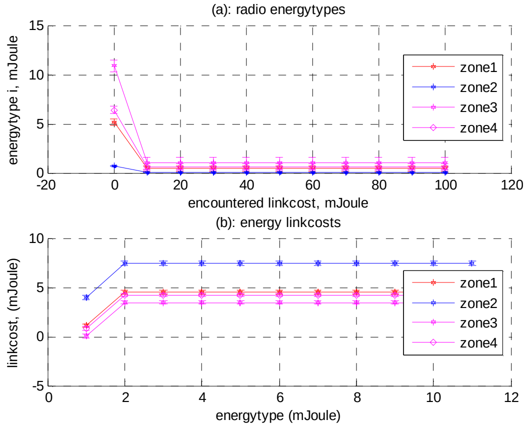

Fig. 1: Average energy link cost types for multi-interface zones: (a) energy types and (b) energy link costs.

In Fig. 2, 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. Fig. 2a 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.

Fig. 2b 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.

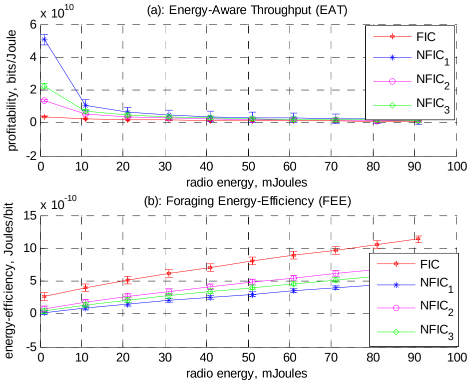

Fig. 2: (a) Average energy-aware throughput and (b) average foraging energy-efficiency versus radio energy cost.

Fig. 3 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. Fig. 3a 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 PSM-MMAC protocol in [5] and the SPWC-PMMUP in [17]. 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. 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 Fig. 3b, 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.

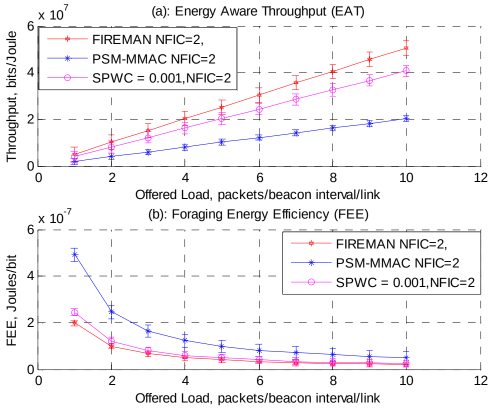

Fig. 3: (a): EAT and (b): FEE versus Offered traffic load per beacon interval.

VII. CONCLUSION AND FUTURE WORK

In conclusion, this paper has presented the FIREMAN method in multi-radio Wi-Fi networks. It involves the protocol and algorithm designs which are inspired by the behaviours of biological foragers. Computer simulations have shown that this method demonstrates better throughput and energy-efficiency performances than conventional methods. Future research involves the extension of the FIREMAN method to the solution of joint dynamic energy and channel assignment in green wireless broadband networks. In such a design, the modified link layer firmware will execute the cross layer energy management for lifetime maximization, while ensuring that the available frequency channels are dynamically assigned to the active communication links. The results found will be applied to large scale heterogeneous networks.

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