Bio-inspired Energy and Channel Management in Distributed Wireless Multi-Radio Networks

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Abstract

In the recent past, research in the next generation wireless heterogeneous broadband networks has favoured the design of multi-radio interface over the single radio interface architectures in order to support desirable features such as a self-organisation, self-configuration, reliability and robustness of network operations in a resource-constrained environment. However, such autonomous network behaviours have been seen to cause an inefficient consumption of energy and frequency channel resources, impacting negatively on the economy and environment. In order to address the inefficient energy and frequency channel utilisation problems, this paper proposes a biological behaviour-based network resource management method. The research is inspired by such a well-established optimal foraging theory whereby a solitary biological forager in a random ecosystem makes optimal decisions that maximise its own nutrients consumption, survival probability and lifetime, while minimising possible risks associated with its own behaviour. The paper has applied this natural principle and developed a Bio-inspired Energy and Channel (BEACH) management method. The BEACH method is aimed at achieving both efficient communication energy and frequency channel utilisation in the considered distributed wireless multi-radio network. The efficacy of the developed BEACH method has been extensively validated through computer simulations and shown to yield improved energy-efficiency and throughput performance.

I. INTRODUCTION

The research in the recent past has witnessed a rapid evolution of wireless networks into the regime of the next generation heterogeneous broadband and mobile multi-radio networks [1]. This has compelled different wireless technologies to co-exist as a single network of peers with ability to be self-organised, self-configured, reliable and robust in resource-constrained environment [2]. However, such agile architectural and functional characteristics have

contributed negatively to the unnecessary energy and frequency channel utilisation [1]. Studies such as [3] and [4] have proposed several green strategies for wireless networking protocols in order to achieve efficient energy and spectrum consumption objectives. However, their designs have not recognised the stringent requirements of the heterogeneous wireless multi-radio multi-channel (MRMC) internet technologies such as scalability and autonomy. These new requirements allow the heterogeneous network to be able to manage architectural and functional complexities efficiently [1]. Motivated by the new operational requirement, this paper proposes a novel Bio-inspired Energy and CHannel (BEACH) management method or simply the BEACH method in order to achieve efficient energy and channel utilisation in a distributed wireless multi-radio network [5].

The main concept comes from the field of behavioural ecology or the biological foraging theory, in which a solitary biological forager in an ecosystem makes optimal decisions that maximise its own rate of the energy gain, while minimising risks associated with its own behaviour. The forager ultimately improves its survival probability and lifetime in a randomly distributed environment of prey types [6]. Using this bio-inspired methodology, a solitary biological forager can be applied in the proposed study to model the network's communication energy and frequency channel resource manager, and the nutrients or prey types mimic the radio communication energy and frequency channel resource types that the wireless radio interfaces must consume in order to exchange packets in a random wireless network. The BEACH method involves the application of the optimal foraging theory such that the radio communication energy (i.e., the energy link costs) and frequency channels are encountered randomly by the wireless radio interfaces. The aim of each radio interface is to devise an optimal algorithm that maximises an energy-aware throughput (EAT) as the network's profit so as to increase its lifetime, while delivering a high capacity. In this case, the radio's profitability can be described by a set of feasible foraging behaviours consisting of optimised resource preference rates and allocation times that should be carefully determined to ensure a significant improvement in the energy and spectrum-efficiency [7]. The performance of the developed BEACH method has been extensively validated through computer simulations of a randomly distributed multi-radio network. Thus, the proposed study can be viewed as an early contribution towards the application of the optimal foraging theory of nutrients optimisation to the field of green and spectrum-efficient wireless internet research.

The remainder of this paper is organised as follows: Related work in the field of radio energy and channel management is discussed in Section II. In Sections III and IV the BEACH system model and the corresponding protocol are developed, respectively. Section V provides the network's throughput and energy-efficiency performance. Conclusions and Future research are given in Section VI.

II. RELATED WORK

The study of the BEACH method has been motivated by a number of interesting experimental results stemming from measurements of the energy consumption behaviours in real Wi-Fi networks [5], [8], [9]. In these studies, the actual impact between the traffic patterns and power consumption as well as an opportunistic spectrum access management has been proposed. Further, studies in [5], [9] presented a 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. 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. The protocol also considered the optimisation of the medium access probability in the p-persistent carrier sense multiple access with collision avoidance (CSMA/CA) used in the data exchange. The protocol, however, assumed that the default radio interface card (RIC) uses 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 BEACH method utilises the link layer protocol [10] 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. Also, the default RIC is enforced to operate in a low power mode to exchange control packets only, while other RICs use power-controlled levels to exchange the application traffic.

The implementation of the BEACH method is closely related to [11] in which the authors presented an energy-efficient multi-radio platform. In this case, an examination of efficient interfaces between the multiple heterogeneous radios and one or more processors on a single sensor node for energy-efficiency was performed. Studies in [1], [10] proposed an autonomous transmission energy adaptation for MRMC wireless mesh networks. The transmission energy was dynamically adapted either asynchronously or synchronously, depending on the delay sensitivity requirement of the application traffic, by each radio interface. The interfaces were coordinated by a power selection MRMC unification protocol (PMMUP) [10]. The transmission energy adaptations were based on the locally residing energy amount in a node, the amount of the application traffic at the local queue, the quality of the links and the interference conditions in the wireless medium [12].

In [12], the inter-channel, co-channel interference, and energy consumption at the queues were modelled as joint singular-perturbation and weakly-coupled (SPWC) systems. In this design, multiple channels formed unified channel graphs with non-conflicting edges but having weakly-coupled effects on the application traffic at the queue. The impact of such queue perturbations on the transmission probability and energy consumption was analysed. Although the SPWC system was energy-aware, it was deemed to be computationally complex and did not address the joint problem of the dynamic channel negotiations and energy-efficiency. This issue has been resolved by the BEACH method via devising an autonomous foraging radio resource allocation (AFRRA) agent that can be implemented at the link layer [1].

Campbell et al. [13] solved the problem of limited non-overlapping frequency channels, delay and congestion at the sink nodes of the wireless sensor networks by providing necessary conditions to verify the feasibility of round robin techniques. They used undirected graph modelling approach in order to regulate multi-radio multi-channel assignment algorithm at the sink nodes. The performance of the developed algorithm was demonstrated via computer simulations and showed that an increase in the number of sink nodes and the number of radio interfaces at the sinks yielded an improved delay and throughput performance at the sink nodes. In [14], a distributed energy-efficient spectrum access and resource allocation in cognitive radio networks was proposed. Each emerging cognitive

radio user selected its frequency subcarriers and determined its transmission parameters individually by solving a constrained optimisation problem in an OFDMA network. In order to reduce the subcarriers detection or search time, a formulated constrained problem was first decoupled into unconstrained problem; an iterative and distributed algorithm for reaching an equilibrium point among multiple transmitter and receiver pairs was then devised. The numerical example considered proved the efficacy of the proposed algorithm. However, there was unreasonable assumption that the subcarriers detection by cognitive radio interfaces was entirely perfect when in reality this might not always be attainable. This condition is considered in the BEACH method by letting that a limited number of non-overlapping channels exist in the considered static wireless network and a fewer number of multiple radio interfaces is switched without incurring significant detection errors. Furthermore, a cache table for temporary storage of topology information has been provided in the BEACH method in order to avoid more often network discovery activities.

Thus, the BEACH method offers a threefold contribution to the existing body of knowledge: 1) a foundational study for applying optimal biological foraging theory of nutrient optimisation to the radio resource management (RRM) problem of wireless multi-radio ad hoc networks; 2) the optimisation of communication energy and frequency channel resources using the well-established optimal foraging theory; 3) the application of the optimal foraging theory to implement green functions of a virtual-MAC layer firmware that is suited to future wireless multi-radio internet technologies.

III. THE BIO-INSPIRED FORAGING BEHAVIOUR MODEL

A. Network resource foraging theory

In behavioural ecology [15], [16], a natural selection may favour "efficient foragers" in an ecosystem that maximise an energy intake or intake of some nutrients or minimise fluctuations in an energy intake, or maximise an energy intake during certain periods. Suppose that an "efficient forager" is attempting to maximise an energy intake, then it must be able to ask and answer the decision-making optimisation questions such as: What types of food will it eat, i.e., how does it make the best recognition strategy?, or where and how long will it search for food, i.e., will it be between patches and within patches of food sources and for how long in terms of time will it cost the forager?, or what type of search path will it use, i.e., will it be random or deterministic [15]?

Any food item has both a cost (i.e., time and energy resources that must be consumed) and a benefit (i.e., the net food value or nutrient that is gained). The relative value of each of these determines how much "profit" a particular food item represents. In other words: "Profit" = the net food value divided by time required to obtain and handle the food item. Efficient foragers must select most profitable food item following a well-established foraging phase cycle (FPC) model illustrated in Fig. 1 [16]. In the biological FPC model, each forager goes through a food search, recognition and an intake phase with a view of achieving the "best strategic foraging behaviour". This simple biological foraging behaviour has recently inspired the application of the theory to wireless network energy optimisation problems [17]. the work exclusively addresses the problem of radio communication energy management,
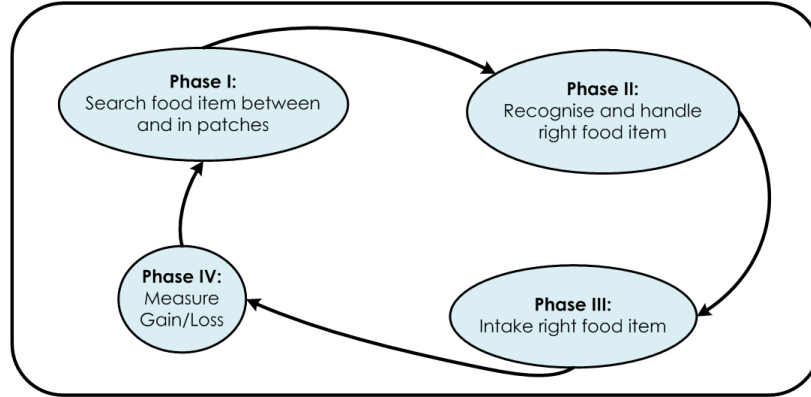
Fig. 1: Foraging Phase Cycle (FPC) model [16].

while the proposed work addresses the problem of channel management jointly with the energy management problem in wireless MRMC - Networks because both are critical network resources to improve performance.

Following a similar argument, the wireless communication networks have the ever dynamic network conditions that may only favour "efficient network elements or agents". Such agents have a goal to either maximise the network capacity or packet delivery ratio or spectrum-efficiency or energy-efficiency and/or lifetime or network coverage or to minimise the latency, delay constraints or packet dropping probability, among others, over a specified period in time [5], [13], [14]. Suppose that an "efficient network agent" is attempting to maximise spectrum-efficiency, then it should be able to ask and answer certain decision-making optimisation questions such as: What type of network resources must it consume i.e., are they time, spectrum, space, communication energy, network radio interfaces or links?, or where and how long will it search for the resources, i.e., will it be external (i.e., in the global or cloud network) or internal (i.e., in the same network) and for how long will the network discovery last?, or what type of search path will it use, i.e., will it be random, deterministic or predictive strategy?

Furthermore, any network resource item has both a cost (i.e., time, spectrum, energy, processing capacity, space, network radio interfaces, etc. that can be consumed or utilised) and a benefit (i.e., the net resource gain achieved by utilising a particular resource item). The relative value each of these determines how much "profit" a particular resource item represents. In other words: "Profit" = change in net resource gain divided by changes in time or spectrum or energy or space, etc, required to discover the network, perform resource optimisation and communicate payload traffic using an optimal resource item and efficient network element should select the most profitable resource item. Each efficient network foraging agent (NFA) needs to go through a cycle consisting of the network association or topology information discovery, an optimal resource management and payload communication phases, referred to as the network foraging phase cycle (NFPC) model in this contribution. The NFPC model as illustrated in Fig. 2, can permit the achievement of the "best strategic resource foraging or management behaviour".

Merits: The NFPC model brings many design benefits when compared to the closely related emerging cognitive
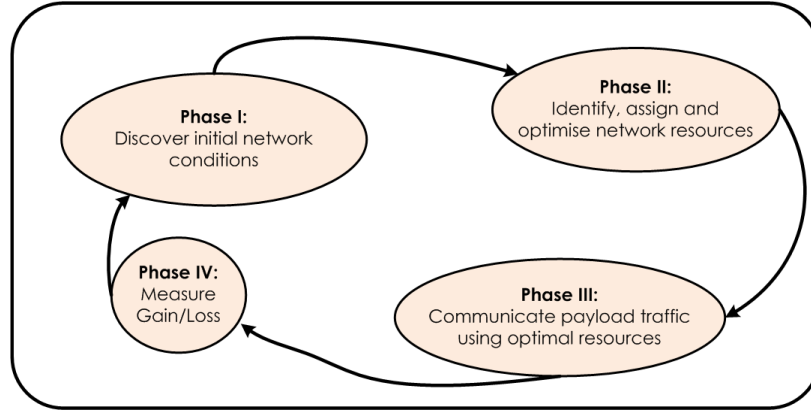
Fig. 2: Proposed Network Foraging Phase Cycle (NFPC) model.

radio models [14], [18]. Firstly, it is likened to a natural selection in a biological ecosystem whereby well-established natural laws are applied. Secondly, it is simple in concept and yet generic enough to be applied in many engineering and wireless network optimisation problems. In fact the researchers in [7] applied this theory successfully to multi-zone temperature control and recently, the authors in [6] adopted this theory to autonomous robotics research. Thirdly, it is computationally efficient method since optimisation variables get eliminated sequentially with increasing iterations and also that the NFPC follows the marginal value theorem (MVT) model. The MVT model is an optimisation model that maximises the expected forager's gain per unit time in systems where resources and rate of returns decrease with time. Thus, the optimal foraging theory weighs the expected benefits and costs involved before pursuing a preferred resource type and it uses the outcome to predict giving up time and giving up density [19]. This means that if a certain resource is perceived to produce low returns, it is rejected automatically and only preferred and profitable resources are pursued further. Lastly, the applied foraging theory offers scalable optimal solutions given that the biological foragers' set and their prey's set are completely decoupled in natural ecosystems.

Demerits: However, the NFPC model may suffer from incidences of suboptimal heuristics in large dense networks. In addition, synchronisation delays may be incurred since the method favours distributed NFA behaviours as opposed to a central arbitration.

B. Graphical optimisation of network resources using the optimal foraging theory

As described in the NFPC, the NFA begins by setting the expected network's benefit objective as an optimisation function of the network resource types such as the communication energy, frequency channel, radio interface, route choices, etc. Due to the inherent generic resource management applications, this function may lack properties required for an analytical tractability and may be optimised graphically as shown in Fig. 3. In Fig. 3, as the network resource types get consumed (i.e., horizontal axis), the resource types become depleted and the rate of returns or profitability evaluated by taking the gradient function along a curve decreases. This foraging behaviour consists of

Fig. 3: Graphical optimisation of the network gain to resource ratio function.

two regions, namely region A in which network resources are searched for (i.e., the NFPC Phase I) and region B (i.e., the NFPC Phase II) in which optimal resource allocations take place. The search and resource allocation regions are functions of time, $\vec{\tau}$ and preference rate, $\vec{p}$ vectors [19]. This means that the applied optimal foraging behaviour should maximise the ratio function of the time and preference dependent gain, $Gr(\vec{p}, \vec{\tau})$ to that of the consumed resource types, $r(\vec{p}, \vec{\tau})$ [19]:

$$J(\vec{p}, \vec{\tau}) \triangleq \frac{Gr(\vec{p}, \vec{\tau})}{r(\vec{p}, \vec{\tau})} = \frac{G_0 + \sum_{i=1}^{n} p_i Gr_i(\tau_i)}{r_0 + \sum_{i=1}^{n} p_i r_i(\tau_i)}. \tag{1}$$

whereby:

The notation, G_0 is the initial gain and r_0 is the initial network resource available at the start of the search or network discovery phase. The notation p_i is the preference rate of a specific resource of type $i \in \{1, 2, \ldots, n\}$ and $Gr_i(\tau_i)$ is the network gain at time τ_i of specific resource of type $i \in \{1, 2, \ldots, n\}$.

Using Fig. 3, it is intuitive to note that each point in region B corresponds to a different feasible behaviour $(\vec{p}, \vec{\tau})$, and the slope of the line connecting that point to $(r_0, -G_0)$, is the value of the objective function $J(\vec{p}, \vec{\tau})$ for that behaviour. Hence, the open circle on a straight line corresponds to a distinct behaviour that results in the same suboptimal rate J^{**}. An optimal behaviour falls on the $(r_0, -G_0)$-ray with the greatest positive slope. Here,

the filled circle on a straight line corresponds to the unique optimal behaviour that results in the optimal rate J^*, which is the slope of the corresponding $(r_0, -G_0)$-ray. Because equation (1) is a ratio, its value can be depicted as the slope of a line, and so an optimisation procedure involves finding the line with the steepest slope as can be discerned by the 2 straight lines in Fig. 3 that are originating from point $(r_0, -G_0)$.

Here, region B is constructed by plotting the point $(\sum_{i=1}^{n} p_i r_i(\tau_i), \sum_{i=1}^{n} p_i Gr_i(\tau_i))$ for every $(\vec{p}, \vec{\tau}) \in \Gamma$. For each of those points, the slope of the line connecting it to the point $(r_0, -G_0)$ is equal to the gain-to-resource function for the corresponding behaviour. So an optimisation consists of rotating a ray originating from $(r_0, -G_0)$ from $\theta = 90°$ toward $\theta = 90°$ and stopping at the angle just before the ray leaves region B for the last time. If $(r_0, -G_0)$ is within the region B, the ray will never leave the region between $\theta = 90°$ and $\theta = 90°$ of rotation, and so the $\theta = 90°$ ray should be used. In general, the region B needs not be convex nor connected, but it should be close in order to produce an optimal point (e.g.it could be a finite set of points).

Deriving insights from and applying the foraging theory and graphical optimisation points discussed above, this paper concentrates its focus to the design and model of the BEACH management method. This focus allows us to conduct an in-depth study of mainly two limited radio resources: communication energy and frequency channels in wireless multi-radio networks. The BEACH method model exploits synergies derived from advantages of the optimal foraging theory and inherent similarities with network radio resource management (RRM) problems.

C. Radio resource allocation using the optimal foraging theory

Suppose the NFA is able to complete allocating $n \in \{1, 2, \ldots\}$ discrete types of distinct radio resources (i.e. communication energy and frequency channels) to all active wireless links in the neighbourhood of that node. Here, the term "neighbourhood" refers to a set of all nodes that are reachable by any other node with maximum communication energy. The resource foraging behaviour would be described by type $i \in \{1, 2, \ldots, n\}$ and corresponding preference rate $p_i \in [0, 1]$, and an average time $\tau_i \geq 0$ for each encountered resource of type i. The optimal behaviour of the NFA maximises the gain-to-resource function or an advantage-to-disadvantage objective function analogous to (1) as:

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

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 $i \in \{1, 2, \ldots, n\}$. This objective function is expressed in terms of network resources as:

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

whereby, for each resource type $i \in \{1, 2, \ldots, n\}$ and a corresponding resource allocation time τ_i, the following notations can be defined: λ_i is the rate of encounter with each resource type $i \in \{1, 2, \ldots, n\}$, w_i^k is the frequency channel bandwidth of resource type i and k^{th} radio interface. The frequency channel bandwidth for a specific k^{th} radio interface is defined as, $w_i^k = 2(f_0^i - f_l^k)$, where $f_l^k = f_0^i - \dfrac{w_i^k}{2}$ is the lower frequency and f_0^l is the middle frequency between the lower and the upper frequency channel bounds. The received signal to noise ratio from a resource type i is denoted as SNR_i^k, O_i^{rate} is the rate of the control message overhead, O_i^{Pow} is the communication energy overhead and the P_i^k is the ith communication energy cost belonging to the kth radio interface. The cost of searching for all resource types is denoted as, C^{search} and is assumed fixed. It is a reasonable assumption since both the communication energy and frequency channel resources are taken as local variables. The nodes in the network are also considered to be static causing limited changes in their network topology information.

Consequently, (3) is a one-on-one compared to (2) as follows:

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

$$a_i(\tau_i \triangleq \lambda_i[2(f_0^i - f_l^k)\log_2(1 + SNR_i^k(\tau_i)) - O_i^{rate}(\tau_i)].$$

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

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

$$e_i \triangleq \sum_{j=1, j \neq i}^{n} \lambda_i[P_i^k - O_i^{Pow}].$$

(4)

Here b_i is the summation of all terms in the numerator not involving the type i and e_i is a similar variable for the denominator of equation (3). Once the objective function in (3) and hence in (4) has been determined, an optimal algorithm is evaluated that finds optimal vectors $\vec{p}^*$ and $\vec{\tau}^*$ producing corresponding optimal radio resources. As typical RRM protocols in WLANs standard [20] fix a constant allocation times, the only changing variable would be $\vec{p}^*$. Hence we evaluate the value p_i^k at which J in (3) is maximum as:

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

(5)

By viewing equation (5), it should be 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, $0 \leq p_i^k \leq 1$. 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,

$$set \ \ p_i = 0 \, if \, a_i/d_i < b_i/e_i$$
$$set \ \ p_i = 1 \, if \, a_i/d_i > b_i/e_i. \tag{6}$$

Here, a_i/d_i defines 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 and frequency channel types are first ranked or sorted according to their profitability such that $a_1/d_1 > a_2/d_2 > \ldots > a_n/d_n$. If type j is included in the forager's "resource allocation pool" (that is, those types that it 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:

$$\frac{\sum_{i=1}^{j} \lambda_i a_i}{\sum_{i=1}^{j} \lambda_i d_i} > \frac{a_{j+1}}{d_{j+1}}. \tag{7}$$

The highest j that satisfies the equation (7) is the least profitable resource type which is included in the pool. On the other hand the least j that satisfies (7) is the preferred resource type that should be selected to improve the performance of the BEACH management method. The applied foraging behaviour is embedded in the MRMC-based BEACH protocol in the next section.

IV.   BEACH PROTOCOL

The bio-inspired foraging behaviour model has been described for solving a forager's optimal decision problem. Due to its analytical simplicity and yet its generic in applications, this decision-making model can tractably be embedded into the legacy ad hoc medium access control (MAC) protocol of the emerging wireless MRMC networks in order to implement distributed coordinated functions (DCFs). It is considered that at each node, there is a virtual MAC layer functionality considered that performs link layer based radio resource manager (RRM) similar to the contributions proposed in [1] and [5]. This virtual MAC layer functionality mimics an autonomous foraging radio resource allocation (AFRRA) agent that exploits the optimal foraging theory to assign communication energy and frequency channels optimally to multiple network interface cards (NICs) and wireless links. The agent also conceals the architectural and functional complexity of the physical layer from the unified upper layer protocol stack [1].

The AFRRA agent also interacts with route selection layer through an address resolution protocol (ARP) module in order to sort routing addressing fields [10]. The AFRRA agent maintains a table of AFRRA messages (AFRRAM) that are necessary for managing network information, while incurring minimal network discovery delays.

This maintenance of the AFRRAM table is likened to a case of biological forager who must memorise its previous foraging environment so as to reduce its future search delays. This likeness has motivated the proposal of the BEACH method, in this contribution. Here, the BEACH method in distributed multi-radio wireless networks consists of the MAC firmware architecture and network resource management functionality. In Fig. 4, a bio-inspired MAC firmware architecture illustrating the behaviour of an MRMC virtual MAC is presented and a corresponding BEACH algorithm is illustrated in Fig. 5. The BEACH algorithm is implemented by the AFRRA agent of Fig. 4. The bio-inspired MAC firmware divides available times into periodic beacon intervals [5] and performs MAC protocol functions during corresponding time phases or windows. The first phase, aims at forming the link layer connection of pair of nodes through performing frequency channel negotiation or contention over multiple channels. The second phase, aims at allocating optimally the network resources (i.e., the communication energy and frequency channels) to the foraging and non-foraging radios with a view of achieving a stable network operation. The third phase aims at transferring the application payload traffic successfully through the wireless links between node pairs using optimal network resources in order to measure the most profitable gain at the expiry of this packet transfer.

Referring to Figs. 4 and 5, the first phase describes when a node has an application payload traffic destined for another node; its AFRRA transmits an AFRRAM using a low power default foraging interface card (FIC) through a foraging frequency channel (FFC) to the intended neighbouring receiver. Meanwhile, the non-foraging interface cards (NFICs) are switched by the AFFRA to the doze mode, while the default FIC grabs the FFC with the least interfered link in order to exchange the AFRRAM over a very short duration. The AFRRAM window is enforced by the AFRRA agent to be short enough just to accommodate the exchange of network management information among neighbours and reduce delays significantly.

The short AFRRAM window is always guaranteed when considering that only one common frequency channel is grabbed as the default channel for the RRM activity and that there is no multiple channels switching over a single radio interface card. Moreover, the AFFRAM table maintains neighbour information such as MAC addresses, the residual and communication energy and frequency channels so that there are less often network topology discoveries. Also, the beacon interval is considered limited as the application payload traffic transfer is supported over parallel radio interfaces.

At the intended receiving AFRRA, the FIC listens omni-directionally on the FFCs to receive the transmitter's communication and residual energy. The NFICs at the intended receiver, on the other hand, are compelled by the receiving AFRRA to remain in the doze mode in order to save some network energy and topology information. If the receiving FIC can hear or sense the AFRRAM from the sending AFRRAs, then it means that that FIC is listening through that FIC and that the FFC is temporary reserved for the duration of the AFRRAM window. Any other listening neighbouring links cannot grab such frequency channel for an application payload transfer.
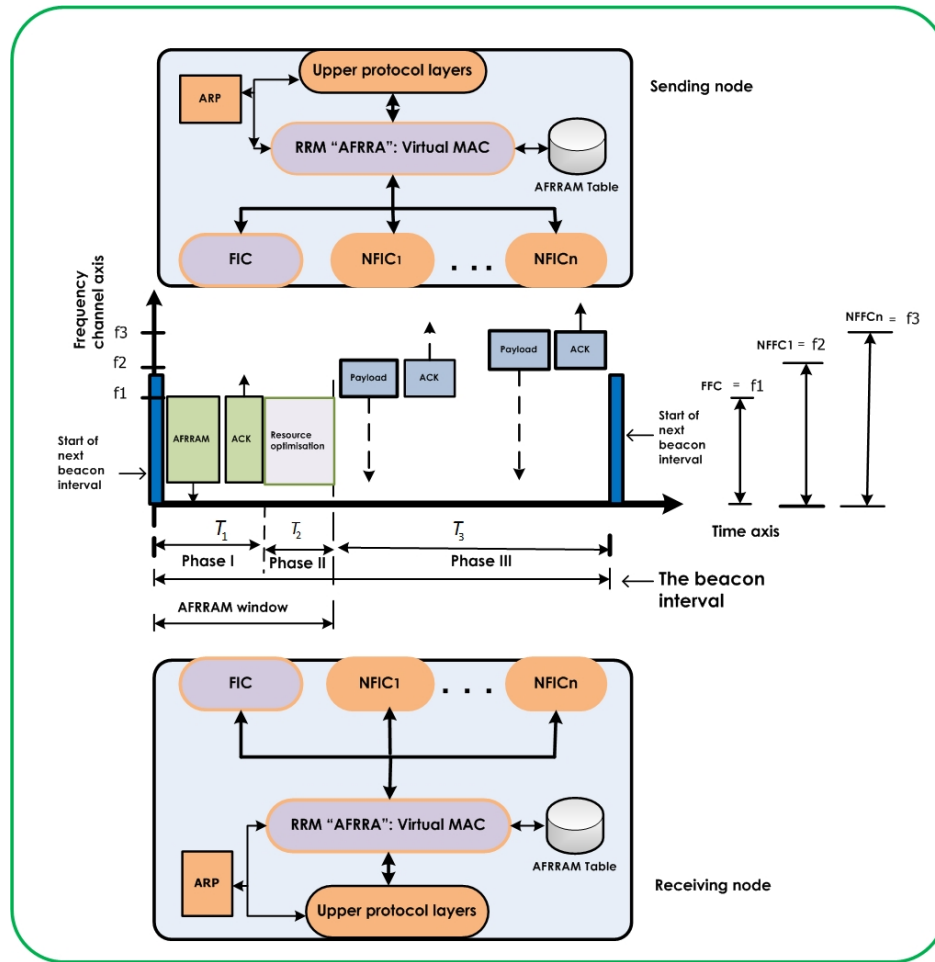
Fig. 4: The proposed Bio-inspired MAC firmware architecture.

The FIC at the intended receiver grabs a frequency channel it detects only if that frequency channel contains the least amount of co-channel interference level and when it also has own MAC address identifying that it is indeed the intended receiver. Otherwise, the receiving FIC rejects any other frequency channel that is overheard with a reasonable co-channel interference level. If the AFRRAM is successfully received, then the receiving FIC replies with AFRRAM-ACK message to the sending AFRRA. Note that all communication energy settings used by other transmitting nodes that are not detected by the receiving FICs imply that they cannot guarantee the neighbourhood connectivity. All frequency channels overheard by the receiving FICs in the neighbourhood that do not contain their own MAC addresses imply that such receiving FICs cannot grab them for transferring the application payload traffic as they are already occupied as FFCs for the exchange of the network management information.

In the second phase, the bio-inspired MAC firmware through the AFRRA utilises the AFRRAM information temporary cached at the AFRRAM table to allocate optimal network resources (i.e., communication energy and frequency channel costs) to the wireless link layer. Optimal estimates of the communication energy and frequency
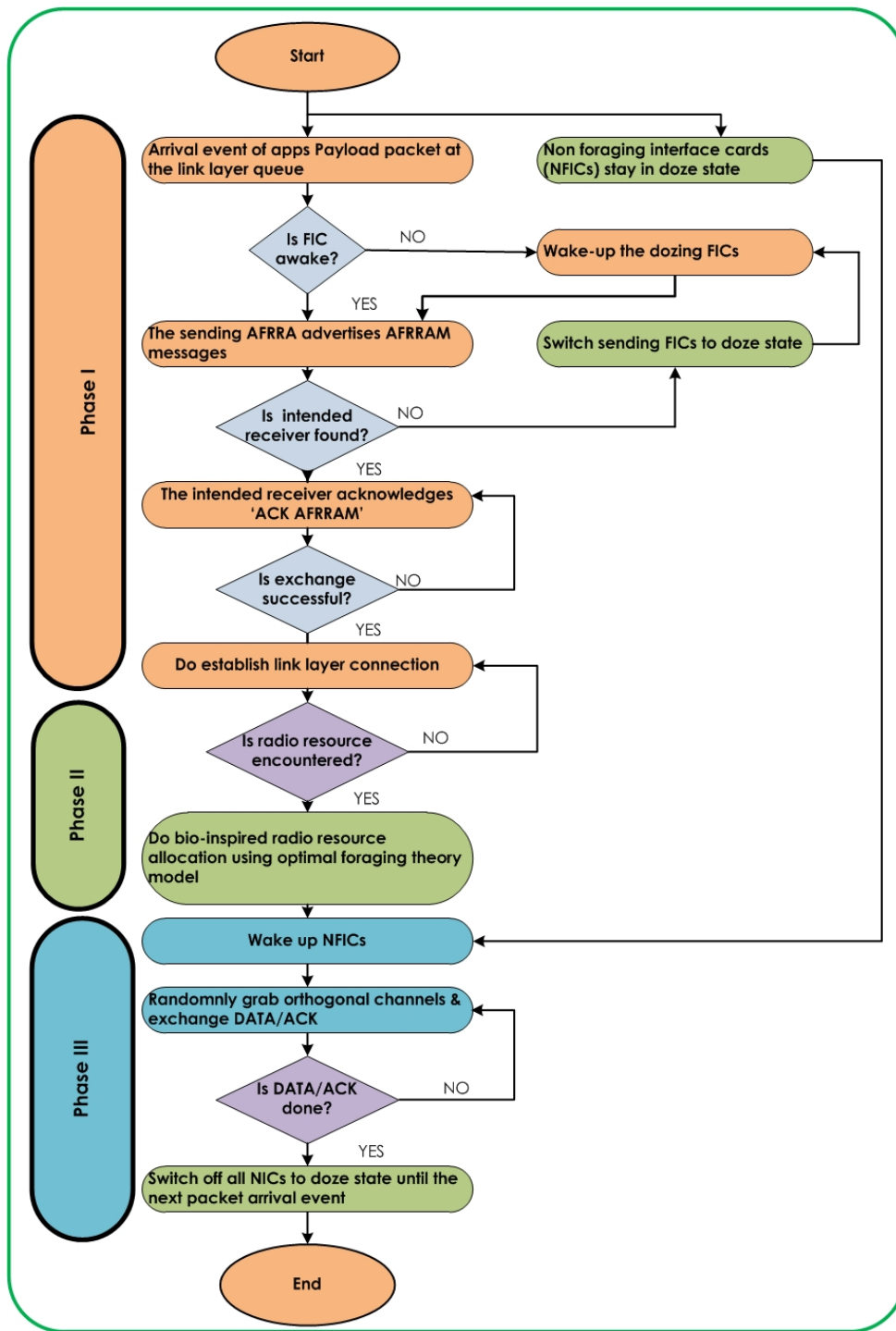
Fig. 5: The Proposed BEACH management method.

channels are determined by executing the iterative foraging allocation behaviour discussed in Section III. The optimal allocation aims at achieving the highest profitable resource that produces the best energy-aware throughput

(EAT) and foraging energy-efficiency (FEE) performance.

In the third phase, the AFRRA agent wakes up the NFICs and switch them randomly to non-overlapping frequency channels at the expiry of the current AFFRAM window. The NFICs then exchange the application payload traffic and the ACK packets with the optimally computed communication energy link costs and over streams of non-overlapping channels. At the end of each beacon interval, all NFICs switch to the doze mode until the arrival of the next application packet at the AFRRA queue.

V. PERFORMANCE EVALUATION

To evaluate the performance of the BEACH management method, several computer simulations of 100 stationary and distributed multi-radio nodes over an area of 400 m by 400 m were conducted. The MATLAB simulator as opposed to the conventional network simulators was used so that more accurate and realistic network conditions could tractably be tested. Also, we leveraged on that the MATLAB simulation tool has the capacity to handle computationally intensive information processing taking into account complex statistics [1]. Specifically, Table I contains the evaluation parameters that were used to demonstrate the performance of the BEACH management method. Each node in the network had up to 4 network interfaces with one interface acting as a default foraging interface card (FIC) for exchanging network management information. The FIC operated through a common foraging frequency channel (FFC), while others operated as the non-foraging interface cards (NFICs) for transferring the application payload traffic over switchable non-foraging frequency channels (NFFCs). Each NFIC was randomly tuned to a non-overlapping frequency spectrum available between 2.412 GHz and 2.484 GHz. The orthogonal channel numbers 1, 6, 11 and 14, each with channel size of 20 MHz belonging to the IEEE 802.11 b/g were considered [20]. The BEACH management procedure followed the bio-inspired foraging behaviour principles developed in Sections III and IV.

The performance evaluation concerning the energy consumption and frequency channel utilisation after a applying the BEACH method was performed for a duration long enough for the output statistics to stabilise (i.e., 60 s). Each datum point in the plots was as a result of averaging 10 data points from 10 simulation runs whereby each run represented a different randomly and normally distributed network topology constituting the same number of the nodes. The network scenarios were based on known source-destination pairs to foster the exploitation of the shorted path routing algorithm and the UDP test traffic [5]. This paper concentrated on the evaluation of effects of the communication energy and frequency channel types on to the energy-aware throughput (EAT) and foraging energy-efficient (FEE) profitability performance.

In Fig. 6, the average energy types and link costs (i.e., the amount of communication energy needed to successfully transmit packets) distributions at the four radio interface zones are shown with a 95% level of confidence. Note that in this paper, the term radio interface zone refers to the locality of the network interface at each node. As the encountered link cost increases, the energy types drops 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,

TABLE I: Performance evaluation parameters

Parameter	Definition and description	Specification
Transmission rate	Basic interface rate for both the AFRRAM and Payload exchanges	2 Mbps
Payload length	Fixed, 456 of Payload, 16 of UDP, 40 of IP	512 bytes
Buffer length	Fixed	50 bytes
Beacon interval	T1: The channel negotiation window	T1, max = 1 ms
	T2: The AFRRAM exchanges window	T2, max = 330 ms, depending on
	T3: The payload exchange window	the AFRRAM traffic in the medium
	T4: The doze mode window. Randomly chosen if the start of the next	T3 = Variable, depending on the
	beacon or the arrival of next application traffic delays by over 10 ms	data traffic in the medium
	(about 1% the beacon interval)	T1+T2+T3 = 1000 ms
Electronics (Tx and Rx)	Transmission and reception electronic energy consumption	50 micro-Joules/bit
No. of active links	Active links per node	Varied from 2 to 4
	Active links per network of 100 nodes	Varied from 200 to 400
No. of channels	Non-overlapping 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
Payload traffic load	Load injected to each link queue from application layers	Varied from 1 to 10 packets/sec/link of constant bit rate (CBR)
MAC overhead	24 bytes of PLCP header (which is transmitted @ 1 Mbps) + 24 bytes of 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

given the available transmission energy settings of a commodity network device, the exponential types distribution function provides an inverse relation with the energy settings. For example, at zone 1, 0 mJoule (corresponds to type 42) and 100 mJoules (corresponds to type 2) in a multi-radio IEEE 802.11b/g. Type 42 signifies the least energy cost consumed by the link, while type 2 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) that are compatible with the most wireless 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].

In Fig. 7, the average performance of the BEACH method with a 95% confidence level, when applied to the radio communication energy allocation in multi-radio network, is depicted. Fig. 7a illustrates the effect of the radio communication energy on the 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 performance drops 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 5 mJoules, the $NFIC_2$ zone provides 250% more throughput profitability than that of the FIC zone, on the average.
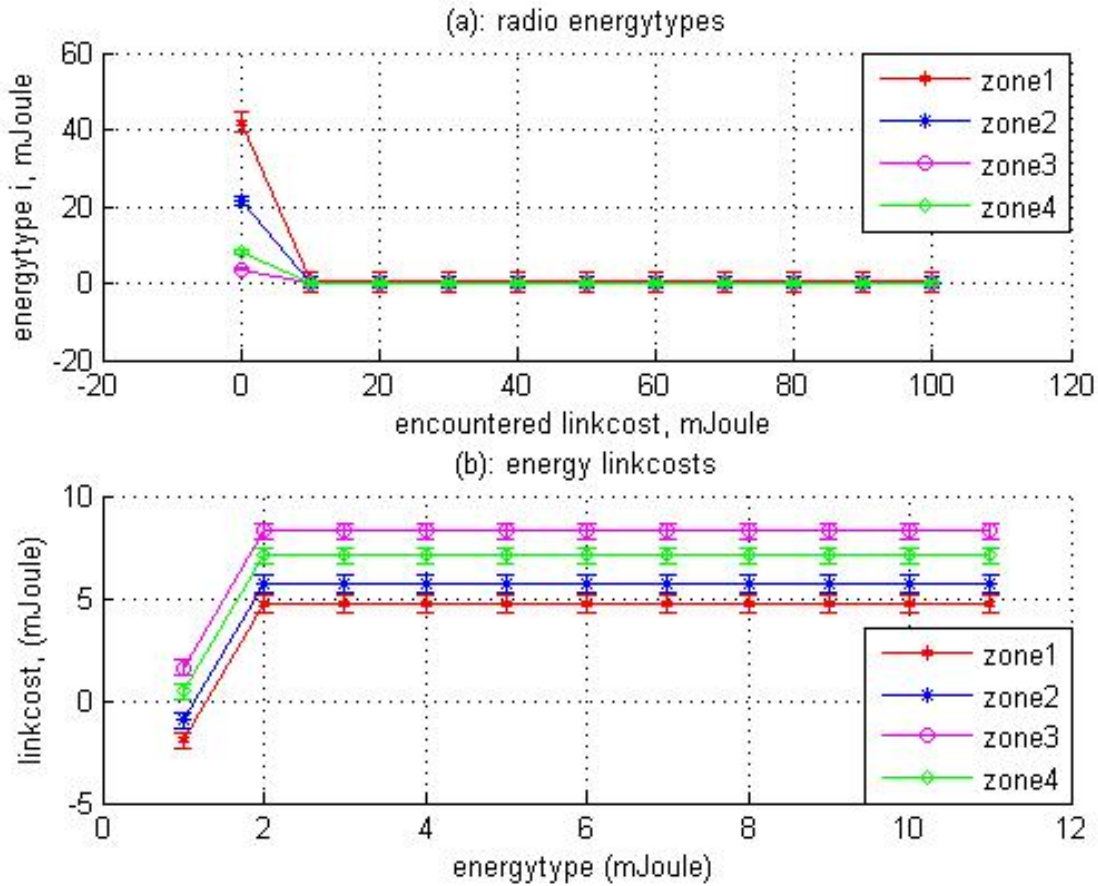
Fig. 6: Average energy link cost types for multi-interface zones: (a) energy types and (b) energy link costs.

Fig. 7b portrays the effect of the radio communication energy on the 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 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 $NFIC_2$ consumes 40% less energy than that of the FIC zone, on the average.

Fig. 8 illustrates the impact of the traffic load offered to each link on the EAT performance and on the corresponding FEE performance. Fig. 8a suggests that more traffic loading onto the link leads to a better EAT
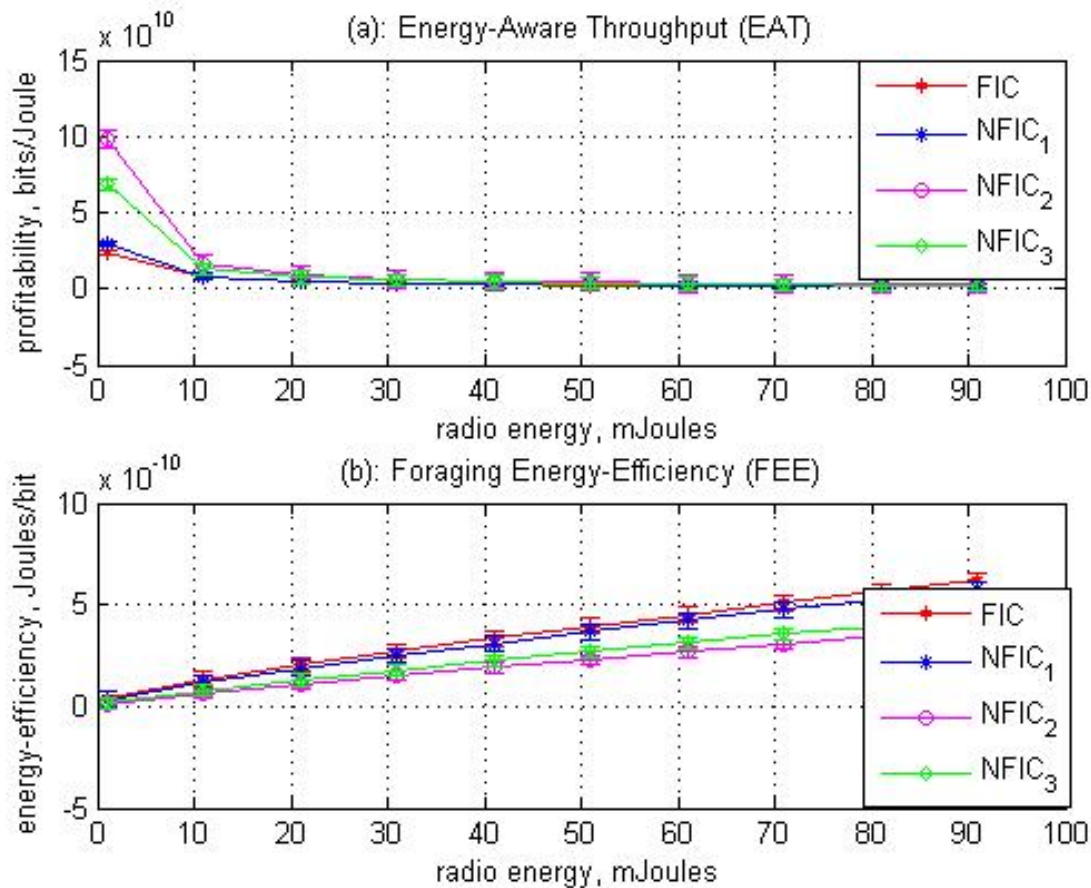
Fig. 7: (a) Average energy-aware throughput and (b) average foraging energy-efficiency versus radio energy cost.

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 BEACH method was compared with the PSM-MMAC protocol in [5] and the SPWC-PMMUP in [12]. The current tests have found that the BEACH 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 BEACH method records 40% 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 BEACH method is capable of making optimal decisions in a random wireless environment. It forces the FIC to exchange the control messages or information, while the NFICs exchange the application payload 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
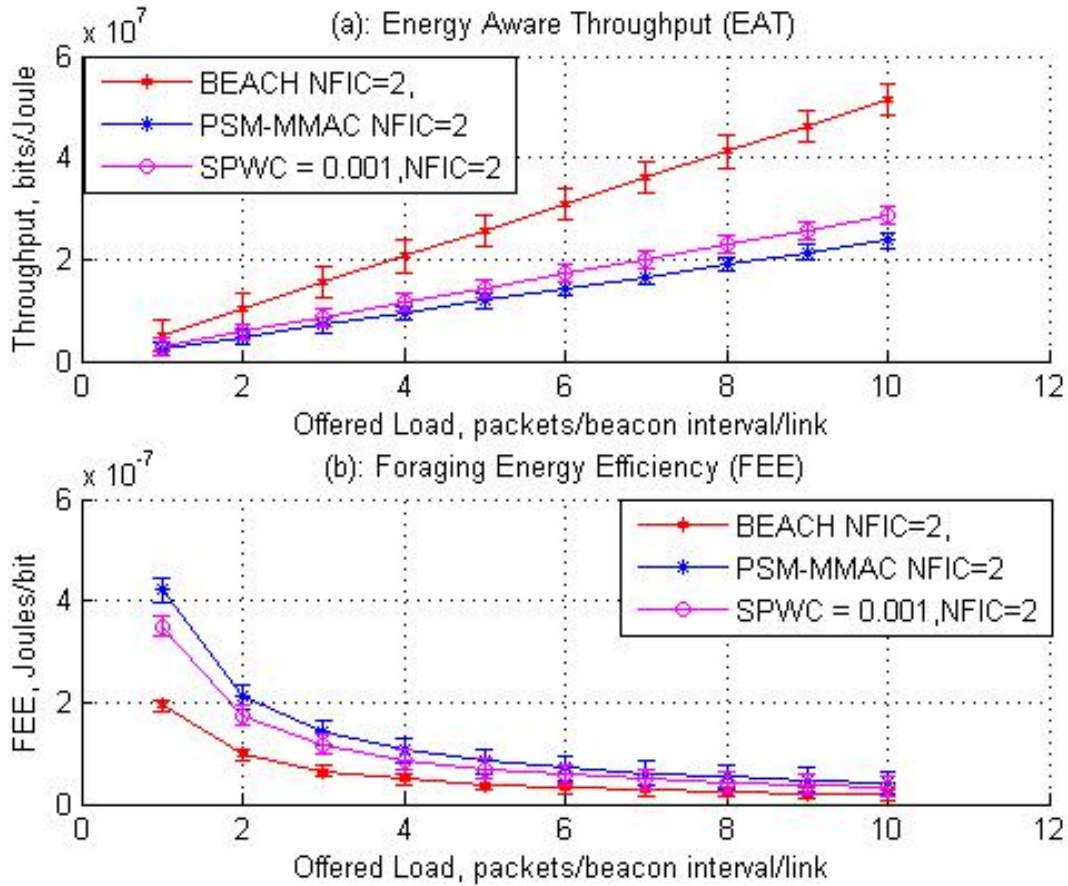
Fig. 8: (a): EAT and (b): FEE versus offered traffic load per beacon interval.

computational time intervals leave less time available for the exchange of application payload traffic. Instead, the BEACH method does the channel assignment such that channels are assigned in every beacon intervals.

In Fig. 8b, a corresponding average FEE performance is shown whereby the BEACH method indicates the best FEE compared to the other conventional methods. Specifically, at 2 packets, on the average, the BEACH method has 40% and 100% better FEE performance than the SPWC-PMMUP and PSM-MMAC methods, respectively. The reason is that the BEACH 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 extra amounts of energy loss. Nodes stay awake only on demand; otherwise they are switched to doze mode.

VI. CONCLUSION

In conclusion, this paper has presented the BEACH method in multi-radio ad hoc networks. It involves the protocol design which is inspired by the behaviours of biological foragers. Computer simulations have shown that

this method demonstrates better throughput and energy-efficiency performances than conventional methods. This bio-inspiration has demonstrated an avalanche of possible open research issues regarding applications of the optimal foraging theory to future wireless internet optimisation problems. In future, the BEACH method contribution will be extended to investigate the effects of optimisation at the link layer on the delay sensitive performance. The modified link layer firmware will be extended to perform the cross-layer scheduling and routing in heterogeneous and multi-hop multi-radio networks for the next generation networks and services.

REFERENCES

[1] Olwal, T.O.: 'Decentralised dynamic power control for wireless backbone mesh networks', PhD Thesis, University of Paris-EST and Tshwane University of Technology, 2010.

[2] Comaniciu, C., Mandayam, N.B., Poor, H.V.: 'Radio resource management for green wireless networks', Proc. IEEE Vehicular Technology Conference, Barcelona, Spain, April 2009.

[3] A.P. Bianzino, A.P., Chaudet, C., Rossi, D.,Rougier, J.L.: 'A survey of green networking research', IEEE Communications Surveys & Tutorials, 2012, 14, (1), pp. 3-20

[4] Tompros, S., Mouratidis, N., Hrasnica, H., Gravras, A.: 'A pervasive network architecture featuring intelligent energy management of households', Proc. 1st ACM International Conference on Pervasive Technnology Related to Assistive Environments (PETRA'08), Athens, Greece, July 2008.

[5] Wang, J., Fang, Y., Wu, D.: 'A power saving multi-radio channel MAC protocol for wireless local area networks', Proc. IEEE INFOCOM, Barcelona, Spain, April 2006, pp. 1-13.

[6] Pavlic, T.P., Passino, K.M.: 'Generalizing foraging theory for analysis and design', International Journal of Robot Research, 2011, 30, (5), pp. 505-523.

[7] Quijano, N.,Passino, K.M.: 'Foraging theory for multi-zone temperature control', IEEE Computational Intelligence Journal & Magazine, 2006, 1, (4), pp.18-27.

[8] Gomez, K., Riggio, R., Rasheed, T., Granelli, F.: 'Analysing the energy consumption behaviour of Wi-Fi networks', Proc. Conference in Green Communications (GreenCom'2011), New York, Sept. 2011, pp. 98-104.

[9] Manweiler, J., Choudhury, R.R.: 'Avoiding the rush hours: Wi-Fi energy management via traffic isolation', IEEE Transaction of Mobile Computing, 2012, 11, (5), pp. 739-752.

[10] Olwal, T.O., van Wyk, B.J., Djouani, K. *et al.*:'Autonomous transmission power adaptation for multi-radio multi-channel wireless mesh networks', Proc. International Conference ADHOC-NOW, Murcia, Spain, September 2009, pp. 284-297.

[11] Lymberopoulos, D., Priyantha, N.B., Goracko, M., Zhao, F.: 'Towards energy-efficient design of multi-radio platforms for wireless sensor networks', Proc. ACM International Conference on Information Processing in Sensor Networks (IPSN'08), St. Louis, Missouri, USA, April 2008.

[12] Olwal, T.O., Djouani, K., Kogeda, O.P., van Wyk, B.J.: 'Joint queue-perturbed and weakly coupled power control for wireless backbone networks', International Journal of Applied Mathematics and Computer Science, 2012, 22, (3), pp. 749-764.

[13] Campbell, C. E. A., Khan, S., Singh, D., Loo, K.K.: 'Multi-channel multi-radio using 802.11 based media access for sink nodes in wireless sensor networks', Sensors, 2011, pp. 4917-4943.

[14] Gao, S., Qian, L., Vaman, D.R.: 'Energy efficient resource allocation in cognitive radio wireless ad hoc networks', in Wang, X. (Ed.): 'Mobile Ad-Hoc Networks: Protocol Design' (2011).

[15]   Stephens, D.W., Brown, J.S., Ydenberg, R.C. (Eds.): 'Foraging: Behaviour and ecology', University of Chicago Press, Chicago, USA, 2007.

[16]   Sweeney, K.: 'Predator and prey activity levels jointly influence the outcome of long-term foraging bouts', Behaviorial Ecology, 2013, 25, (5), pp. 1205-1210.

[17]   Olwal, T.O., van Wyk, B.J., Kogeda, P. O., Mekuria, F.: 'FIREMAN: Foraging-inspired radio communication energy management in green multi-radio networks', in Khan, S., Mauri, J.L. (Eds.), Green Networking and Communications: ICT for sustainability (Auerbach publications, Francis and Taylors Group, CRC Press, 2013) pp. 29-47.

[18]   Halder N., Song, J.B: 'Game theoretical analysis of radio resource management in wireless networks: a non-cooperative game approach of power control', International Journal of Computer Science and Network Security, 2007, 7, (7), pp. 184-192.

[19]   Pavlic, T.P.: 'Optimal Foraging Theory Revisited', MSc thesis, The Ohio State University, Columbus, OH, 2007.

[20]   IEEE Standard 802.11, 'Part 11: Wireless LAN medium access control and physical layer specifications', 2012.