Biological Foraging-Inspired Communication in Intermittently Connected Mobile Cognitive Radio Ad Hoc Networks

Baris Atakan, *Member, IEEE*, and Ozgur B. Akan, *Senior Member, IEEE*

***Abstract*—Intermittently connected mobile cognitive radio ad hoc networks (IMCRNs) are promising wireless networks in which mobile unlicensed nodes use their temporarily available contacts and vacant licensed channels for end-to-end message delivery. In this paper, we propose biological foraging-inspired communication (BFC) algorithm for the energy-efficient and spectrum-aware communication requirements in IMCRNs. BFC is based on two profitability measures called *relay selection profitability* (RSP) and *channel selection profitability* (CSP). RSP and CSP provide an autonomous decision-making mechanism that does not need any *a priori* information on node mobility and spectrum availability patterns. This decision-making mechanism also leads to an optimization procedure to determine optimal relay and channel selection rules. Performance evaluations reveal that BFC enables each node to determine and regulate its transmission strategy to provide minimum energy consumption without sacrificing end-to-end delay performance. BFC also maximizes overall spectrum utilization in a way that any idle channel is always allocated by a node within a delay bound.**

***Index Terms*—Biologically inspired communication, cognitive radio (CR), foraging theory, intermittently connected mobile networks (ICMNs).**

I. Introduction

UTILIZATION of the wireless spectrum have recently stimulated unlicensed communication in intermittently connected networks (ICN) via cognitive radio (CR) technology. Intermittently connected mobile CR ad hoc networks (IMCRNs) can be viewed as a promising example of ICNs with CR technology. IMCRNs allow intermittently connected mobile unlicensed nodes to exploit temporarily available contacts and idle licensed channels for end-to-end message delivery. However, the realization of IMCRNs also brings crucial research challenges that must be addressed. In particular, due to different node mobility and spectrum availability patterns, an IMCRN is frequently divided into unpredictable partitions. These partitions are intermittently connected and deficient in complete end-to-end paths. Hence, the realization of IMCRNs necessitates addressing intermittent and spectrum-aware communication.

There is an emerging body of literature on routing protocols in CR ad hoc networks [1]–[6]. All of these protocols are based on the assumption that at least one end-to-end path always exists between any two nodes in the network. However, this assumption is invalid for an IMCRN that is usually lacking in complete end-to-end paths. Hence, *spectrum-aware flooding* (SAF) is more relevant for IMCRNs. In SAF, a message is first copied to a set of relay nodes using available channels. Then, one of these relay nodes delivers the message to the destination provided that it encounters. Clearly, if the message is tried to be copied to all relays that do not have the message, the end-to-end message delay can be minimized. However, such a forwarding strategy is energy inefficient and may cause severe interference to a primary system. Hence, it is imperative to decide which relay nodes and licensed channels should be used to mitigate the energy consumption and high interference for an efficient communication in IMCRNs.

In this paper, based on *a prey model in foraging theory*, a biological foraging-inspired communication (BFC) algorithm is introduced. BFC uses two profitability measures called *relay selection profitability* (RSP) and *channel selection profitability* (CSP). The aim of RSP is to allow each node to quantify its gain in copying a message to a relay while examining its transmission effort. Using RSP, each node decides which relays should be used to provide minimum energy consumption without sacrificing end-to-end delay performance. Based on CSP, each node decides and switches to a licensed channel to maximize spectrum utilization while keeping the interference at a minimum level. BFC maximizes overall spectrum utilization in a way that any idle channel is always allocated by an IMCRN node within a delay bound. BFC provides great autonomy for IMCRN by adaptively regulating and tuning its communication strategy. This eventually enables IMCRN nodes to determine optimum relays and channels for an efficient communication in IMCRNs.

Next, the network model and assumptions are introduced. In Section III, a prey model in foraging theory is discussed, and the BFC algorithms are introduced in Section IV. The performance evaluation of BFC is presented in Section V. Finally, concluding remarks are given in Section VI.

Manuscript received October 4, 2011; revised February 29, 2012; accepted April 6, 2012. Date of publication May 11, 2012; date of current version July 10, 2012. The review of this paper was coordinated by Prof. V. W. S. Wong.

The authors are with the Next-Generation and Wireless Communications Laboratory, Department of Electrical and Electronics Engineering, Koç University, Istanbul 34450, Turkey (e-mail: batakan@ku.edu.tr; akan@ku.edu.tr).

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Digital Object Identifier 10.1109/TVT.2012.2198928

II. Network Model and Assumptions

We consider a network with N mobile unlicensed nodes that move in an environment according to some stochastic mobility models. We also assume that the entire spectrum is divided into a number of M nonoverlapping orthogonal channels having different bandwidths. The access to each licensed channel is regulated by fixed-duration time slots. Slot timing is assumed to be broadcast by the primary system. Before transmitting its message, each transmitter node, which is a node with the message, selects a relay node and a frequency channel to copy the message. Note that the details of the selection are given in Section IV. After the relay and channel selection, the transmitter node negotiates and handshakes with its relay node and declares the selected channel frequency to the relay. The communication needed for this coordination is assumed to be accomplished by a fixed-length frequency hopping sequence (FHS) that is composed of K distinct licensed channels. In each time slot, each node consecutively hops on FHS within a given order[1] to transmit and receive a *coordination packet*. The aim of the coordination packet that is generated by a node with the message is to inform its relay about the frequency channel decided for the message copying. Furthermore, the coordination packet is assumed to be small enough to be transmitted within a slot duration. Instead of a common control channel, FHS provides a diversity to be able to find a vacant channel that can be used to transmit and receive the coordination packet. If a hop of FHS, i.e., a channel, is used by the primary system, the other hops of FHS can be tried to be used to coordinate. This can allow the nodes to use K channels to coordinate with each other rather than a single control channel.

Whenever any two nodes are within their communication radius, they are called as contacted. To announce its existence, each node periodically broadcasts a beacon message to its contacts using FHS. Whenever a hop of FHS is vacant, each node is assumed to receive the beacon messages from their contacts that are transiently in its communication radius. This allows each node to keep its temporarily changing contact list using vacant hops of FHS.

Definition 2.1 (Utility for Message Delivery): The utility v_{jd} is a metric that implicitly specifies the message delivery performance of node j if it tries to deliver a message to node d. v_{jd} consists of two parts given as $v_{jd} = v_{jd}^t + v_{jd}^s$. The first part v_{jd}^t characterizes the transient utility, whereas the second part v_{jd}^s characterizes the steady-state utility. By initially setting $v_{jd}^t = 0$ and $v_{jd}^s = 0$, in each time interval I, each node j computes $v_{jd}, \forall d$ using the following utility update strategy.

- If node j contacts with node d at the time interval I, it updates the transient and steady-state components of v_{jd} as $v_{jd}^t = v_{jd}^t + \xi_1$ and $v_{jd}^s = v_{jd}^s + \xi_2$, where ξ_1 and ξ_2 are positive constants.
- If node j does not contact with node d, it just updates the transient part as $v_{jd}^t = v_{jd}^t - \xi_1$. Here, the lower bound of v_{jd}^t is assumed to be zero such that if the update $v_{jd}^t = v_{jd}^t - \xi_1$ makes v_{jd}^t less than zero, v_{jd}^t is immediately set to zero, and the update is skipped as long as $v_{jd}^t = 0$.

[1]The order of FHS order is assumed to be broadcast by the primary system.

As will be introduced, the given utility metric is used by IMCRN nodes to determine their message copying strategies. Next, we brief a prey model in foraging theory, upon which we develop the BFC algorithm for IMCRNs.

III. Prey Model in Foraging Theory

Foraging theory mathematically characterizes how foraging animals search for prey types and decide which prey types will be handled [7]–[10]. Based on these characterizations, the foraging strategies of animals are also adopted and modeled as an optimization process that is referred to as *optimal foraging theory*. For example, this optimization allows a forager to decide the most appropriate prey types so as to maximize the overall energy intake within the minimum time interval.

Among the foraging models, one of the most common models is the prey model. The prey model assumes that there are k different types of prey. t_i is the expected time required to seek and handle prey type i, and ν_i is the expected amount of energy intake obtained by handling prey i. The average rate of encounter with prey i in a searching process is λ_i. p_i is the probability that prey type i is handled once it is found and recognized. Hence, the average rate of gain of a forager, i.e., J, can be defined as a ratio of expected energy intake to expected time spent. This is expressed as

$$J = \frac{\sum_{i=1}^{k} p_i \lambda_i \nu_i}{\sum_{i=1}^{k} p_i \lambda_i t_i}. \tag{1}$$

The maximization of the rate of gain, i.e., J, clearly involves finding the optimal values of p_i $\forall i$. As introduced in the following sections, the prey model provides an efficient zero-one rule to determine the optimal values of $p_i \forall i$. Here, we notice that the foraging theory establishes a solid basis for design of solution approaches to many control and optimization problems.

IV. Biological Foraging-Inspired Communication in Intermittently Connected Mobile Cognitive Radio And Ad Hoc Networks

Here, we first present the analogies between the prey model and IMCRNs. Then, based on the given analogies, we introduce the BFC algorithm.

A. Inspiration from Prey Model

To create a BFC model for IMCRNs, we consider the network nodes to be foragers. Similar to a biological forager searching for prey, each node with a message searches for possible relay nodes to copy its message. Hence, possible relay nodes of a node are considered as prey types in the prey model. Inspired by the prey model, we define a profitability measure named as *RSP*. Using RSP, each node having a message selects its relay nodes to provide a sufficient level of end-to-end latency while examining its transmission effort.

We also consider available licensed channels as prey types and define another profitability measure called *CSP*. Based on CSP, each node selects and uses licensed channels to maximize spectrum utilization with minimum interference to the primary system. Next, RSP and CSP measures are derived.

B. RSP

In the prey model, forager i needs the time duration t_j to search for and handle prey type j. t_j also implicitly corresponds to an amount of energy that forager i consumes in searching and handling prey type j. If forager i handles prey type j, it also gains an expected energy intake, i.e., ν_j, as introduced in Section III. Similar to a forager, IMCRN node i with a message also needs an amount of energy e_{ij} to copy the message to relay node j. If node i copies the message to node j, it also gains the utility v_{jd} to deliver the message to destination node d. Note that v_{jd} has been defined in Section II.

Hence, assuming that node i copies its message to each node j with the probability p_{ij}, the rate of gain of node i, i.e., $\mathcal{G}_i$, can be expressed as

$$\mathcal{G}_i = \frac{\sum_{j \in S_i} p_{ij} v_{jd}}{\sum_{j \in S_i} p_{ij} e_{ij}} \tag{2}$$

where the numerator of $\mathcal{G}_i$ denotes the expected utility gained by copying the message to the selected relay nodes, whereas the denominator is the expected energy consumed by copying the message to the relays. S_i is the contact set that includes IDs of nodes in the communication radius of node i. By finding optimal p_{ij} values, $\mathcal{G}_i$ can be maximized. This also enables node i to copy the message to the most appropriate relay nodes with high utility values by consuming minimum energy. These relay nodes with high utility can also minimize the end-to-end message delay. To show this, let us assume that node i copies the message to relay node j and relay node j encounters with destination node d with probability α in each time interval I. The expected increase in v_{jd} in each time interval I, i.e., u, can be given as

$$\begin{aligned} u &= \alpha(\xi_1 + \xi_2) - (1-\alpha)\xi_1 \\ &= \alpha(2\xi_1 + \xi_2) - \xi_1 \end{aligned} \tag{3}$$

u is a strictly increasing function of α. On the other hand, using α, the expected number of time intervals I in which relay node j meets with destination node d, i.e., γ, can be also found as

$$\gamma = \sum_{i=1}^{\infty} i\alpha(1-\alpha)^{i-1} = \frac{1}{\alpha}. \tag{4}$$

As observed in (4), γ is a strictly decreasing function of α. Consequently, by combining the results obtained in (3) and (4), it can be shown that the expected delay of node j to encounter with destination node d can be minimized by maximizing v_{jd}. Thus, the aim of node i is to maximize $\mathcal{G}_i$ by choosing optimal p_{ij} values. This can be formulated as follows:

$$\underset{p_{ij}\in[0,1]}{\boldsymbol{argmax}}\ \mathcal{G}_i \tag{5}$$

where each selection event is considered a Bernoulli random variable, i.e., $p_{ij} \in [0,1]$. Hence, the constraint $\sum_{j\in S_i} p_{ij} = 1$ is not required to be satisfied in the selection of p_{ij} values.

For the solution of (5), $\mathcal{G}_i$ in (2) can be rewritten as

$$\mathcal{G}_i = \frac{p_{ij}v_{jd} + \eta_i}{p_{ij}e_{ij} + \kappa_i} \tag{6}$$

where η_i and κ_i can be expressed as

$$\eta_i = \sum_{\substack{z\in S_i \\ z\neq j}} p_{iz}v_{zd} \qquad \kappa_i = \sum_{\substack{z\in S_i \\ z\neq j}} p_{iz}e_{iz}. \tag{7}$$

For the optimal p_{ij}, (6) can be differentiated as

$$\begin{aligned} \frac{\partial \mathcal{G}_i}{\partial p_{ij}} &= \frac{v_{jd}(\kappa_i + p_{ij}e_{ij}) - e_{ij}(\eta_i + p_{ij}v_{jd})}{(\kappa_i + p_{ij}e_{ij})^2} \\ &= \frac{v_{jd}\kappa_i - e_{ij}\eta_i}{(\kappa_i + p_{ij}e_{ij})^2}. \end{aligned} \tag{8}$$

Based on the differentiation in (8), p_{ij} can be found to maximize $\mathcal{G}_i$ by the following way:

- If $(v_{jd}/e_{ij}) < (\eta_i/\kappa_i)$ is satisfied, $(\partial \mathcal{G}_i/\partial p_{ij})$ is negative, and $\mathcal{G}_i$ can be maximized by choosing the lowest possible p_{ij}, i.e., $p_{ij} = 0$.
- Conversely, if $(v_{jd}/e_{ij}) > (\eta_i/\kappa_i)$ is satisfied, $(\partial \mathcal{G}_i/\partial p_{ij})$ is positive, and $\mathcal{G}_i$ can be maximized by choosing the highest possible p_{ij}, i.e., $p_{ij} = 1$.

Consequently, the selection of p_{ij} to maximize $\mathcal{G}_i$ leads to a zero-one rule as follows:

$$\begin{aligned} &\textbf{set} \quad p_{ij} = 0 \quad \textbf{if} \quad \frac{v_{jd}}{e_{ij}} < \frac{\eta_i}{\kappa_i} \\ &\textbf{set} \quad p_{ij} = 1 \quad \textbf{if} \quad \frac{v_{jd}}{e_{ij}} > \frac{\eta_i}{\kappa_i} \end{aligned} \tag{9}$$

where (v_{jd}/e_{ij}) is the *RSP* and characterizes how much benefit node i gets if it uses node j as a relay to deliver the message to destination node d.

C. CSP

Here, we derive the CSP measure to permit IMCRN nodes to decide which licensed channels should be used. The aim of CSP is to maximize spectrum utilization with minimum interference to the primary system. Assume that there are M licensed channels with different bandwidth values and ω_c denotes the bandwidth of channel c. Each IMCRN node is also assumed to periodically sense a set of M licensed channels. A_i denotes the set including IDs of licensed channels that are periodically sensed by node i. Suppose that channel c is periodically sensed by node i in each slot and channel c is idle during the time interval ρ_c called *channel idle duration*. Here, we use the product of channel bandwidth ω_c and the channel idle duration ρ_c, i.e., $\mathcal{E}_c = \omega_c\rho_c$, as a metric to examine the channel idleness. Furthermore, failures in the sensing of primary users are assumed to cause the collisions among the transmissions of primary users and IMCRN nodes. Such collisions are also assumed to impose an interference level on the primary system. As the primary-user activities become heavy, the likelihood of the collisions increases; thus, the interference level also increases. Let n_{ic} denote the interference level incurred by node i if it uses the channel c. Hence, the total rate of gain of node i in licensed channel selection, i.e., $\mathcal{C}_i$, is given as the ratio of expected $\mathcal{E}_c$ to expected n_{ic}, i.e.,

$$\mathcal{C}_i = \frac{\sum\limits_{c \in A_i} a_{ic}\mathcal{E}_c}{\sum\limits_{c \in A_i} a_{ic} n_{ic}} = \frac{\sum\limits_{c \in A_i} a_{ic}\omega_c\rho_c}{\sum\limits_{c \in A_i} a_{ic} n_{ic}} \tag{10}$$

where a_{ic} is the probability that node i uses channel c. a_{ic} is also a decision variable for node i. The maximization of $\mathcal{C}_i$ clearly allows node i to use mostly idle licensed channels with high bandwidth while minimizing the expected interference level. Thus, the aim of node i is to maximize $\mathcal{C}_i$ by solving

$$\underset{a_{ic} \in [0,1]}{\boldsymbol{argmax}}\ \mathcal{C}_i. \tag{11}$$

For this aim, (10) can be rewritten as follows:

$$\mathcal{C}_i = \frac{a_{ic}\omega_c\rho_c + \zeta_i}{a_{ic}n_{ic} + \lambda_i} \tag{12}$$

where ζ_i and λ_i are

$$\zeta_i = \sum_{\substack{z \in A_i \\ z \neq c}} a_{iz}\omega_z\rho_z \quad \text{and} \quad \lambda_i = \sum_{\substack{z \in A_i \\ z \neq c}} a_{iz} n_{iz}. \tag{13}$$

Similar to the zero-one rule in the derivation of the RSP given in (6)–(9), the selection of a_{ic} for maximizing $\mathcal{C}_i$ leads to a zero-one rule, i.e.,

$$\begin{array}{llll} \textbf{set} & a_{ic} = 0 & \textbf{if} & \dfrac{\omega_c\rho_c}{n_{ic}} < \dfrac{\zeta_i}{\lambda_i} \\ \textbf{set} & a_{ic} = 1 & \textbf{if} & \dfrac{\omega_c\rho_c}{n_{ic}} > \dfrac{\zeta_i}{\lambda_i} \end{array} \tag{14}$$

where $(\omega_c\rho_c/n_{ic})$ is the *CSP* and characterizes how much benefit node i gets if it uses channel c. Next, using the results summarized in (9) and (14), we introduce the relay selection and channel selection algorithms in BFC.

Algorithm 1: BFC: Relay Selection Algorithm

while $Hop\ Count < 3$ **do**
  foreach *Node i with Message* **do**
    computes RSP for each contact
    while *Total Energy Consumption* $< E$ **do**
      copy message to a relay j that satisfies $p_{ij} = 1$ in (9)
      update η_i and κ_i in (7)
      update total energy consumption by adding e_{ij}
    end
  end
end

D. Relay Selection Algorithm in BFC

BFC selects the relay nodes within only three hops. The source node first copies the message to a set of relay nodes that it encounters, and these relay nodes also follow the same strategy with the source node. Then, one of the relay nodes having the message immediately delivers the message to the destination node d, provided that it meets. BFC allows each node to copy the message using a predefined energy budget called E. After the depletion of E, the nodes stop copying the message. The relay selection is accomplished via the zero-one rule given in (9). Let us assume that node i with the message encounters with node j and receives the utility value v_{jd} from node j. To decide whether it copies the message to node j, node i first computes the energy needed for delivering the message to node j. Here, we assume that each node i discovers the locations of its contacts using one of the existing localization methods[2] in the literature [12]. By using the location information, it also computes the Euclidean distances to its neighbors. Let l_{ij} be the Euclidean distance between node i and j. Using l_{ij}, node i computes energy e_{ij} required to deliver the message to node j as $e_{ij} = o + rl_{ij}^s$, where s is a positive constant that characterizes the power loss in wireless transmission and o is the dissipated energy in the transmitter circuitry. r is the energy needed by the transmitter amplifier [13]. Hence, as node i meets with relay nodes and discovers v_{jd} and e_{ij} $\forall j \in S_i$, it decides whether to copy the message to relay node j by directly using the zero-one rule given in (9) as follows. Initially, it first copies the message to the first contact it meets. Then, whenever a contact satisfies the zero-one rule, node i copies the message of that contact and updates η_i and κ_i in (7). Then, it continues to check whether its remaining contacts satisfy the zero-one rule by considering the updated η_i and κ_i. Furthermore, node i also updates and checks its residual energy budget whenever it copies the message to a relay node. If it depletes all of its energy budget E, it immediately stops copying the message. Here, we also notice that the BFC relay selection algorithm is represented for the case in which there is only one source in the network. However, it can be easily extended for multisource cases by using the same algorithm steps for each source node. The relay selection algorithm in BFC is also outlined in Algorithm 1.

Algorithm 2: BFC: Channel Selection Algorithm

foreach *Channel c in* A_i **do**
  determine ρ_c, ω_c, and n_{ic}
end
foreach *Channel c in* A_i **do**
  if $\{c \mid \forall k \in A_i : (\omega_k\rho_k/n_{ik}) < (\omega_c\rho_c/n_{ic})\}$ **then**
    select channel c for message copying
  end
end

E. Channel Selection Algorithm in BFC

In BFC, the channel selection follows the zero-one rule given in (14). Each node i periodically senses a set of all

[2]The details of localization procedure are beyond the scope of this paper.

available licensed channels,[3] and it determines and updates the idle duration of all sensed channels, i.e., $\rho_c \forall c \in A_i$. The bandwidth of each channel, i.e., $\omega_c \forall c$, is assumed to be known by all IMCRN nodes. For each sensed channel, node i is also assumed to estimate the interference level (n_{ic}) that it imposes on a channel if it uses this channel.[4] Hence, using ω_c, ρ_c, and n_{ic}, node i computes all CSP values and selects channel c such that $\{c \mid \forall k \in A_i : (\omega_k \rho_k / n_{ik}) < (\omega_c \rho_c / n_{ic})\}$. Such a selection strategy does not conflict with the zero-one rule in (14). Inherently, it usually satisfies $(\omega_c \rho_c / n_{ic}) > (\zeta_i / \lambda_i)$, as given in (14). The channel selection algorithm in BFC is also outlined in Algorithm 2.

Lemma 1: The channel selection algorithm of BFC enables each idle licensed channel c to be definitely allocated by an IMCRN node within a time duration, i.e., τ, such that τ always has an upper bound, i.e., τ_u, that can be expressed as

$$\tau_u = \frac{\omega_{\max} n_{ic} m}{\omega_{\max} n_{ic} - \omega_c n_{\min}} \tag{15}$$

where $n_{\min}$ and $n_{\max}$ are the minimum and maximum of the interference, i.e., $n_{\min} \le n_{ic} \le n_{\max} \forall i, c$. $\omega_{\max}$ is the maximum of all channel bandwidth values, i.e., $\omega_c \le \omega_{\max}$ $\forall c$. Furthermore, m is the average time duration required for successfully transmitting the message to a relay.

Proof: Assume that, at a time instant, channel c has been unused during τ and all of other channels are used at least once within τ. In this time instant, the CSP of channel c, i.e., ψ_{ic}, can be computed by any node i as

$$\psi_{ic} = \frac{\omega_c \rho_c}{n_{ic}} = \frac{\omega_c \tau}{n_{ic}} \tag{16}$$

In addition, suppose that channel k has the maximum CSP at this time instant. Since channel k has been used at least once within τ, the possible maximum value for ρ_k can be given as $\rho_k = \tau - m$. Channel k may also have the maximum bandwidth, and any node j may incur the minimum interference to the primary system if it uses channel k. In this case, ω_k and n_{jk} can be considered as $\omega_k = \omega_{\max}$ and $n_{jk} = n_{\min}$, respectively. Hence, by setting $\rho_k = \tau - m$, $\omega_k = \omega_{\max}$, and $n_{jk} = n_{\min}$, node j computes the CSP of channel k, i.e., ψ_{jk}, as follows:

$$\psi_{jk} = \frac{\omega_{\max}(\tau - m)}{n_{\min}}. \tag{17}$$

To ensure that channel c is used before channel k

$$\begin{aligned} \psi_{ic} &> \psi_{jk} \\ \frac{\omega_c \tau}{n_{ic}} &> \frac{\omega_{\max}(\tau - m)}{n_{\min}} \end{aligned} \tag{18}$$

has to be satisfied, provided that

$$\tau < \tau_u = \frac{\omega_{\max} n_{ic} m}{\omega_{\max} n_{ic} - \omega_c n_{\min}} \tag{19}$$

■

In IMCRNs, successful channel utilization of a transmitter depends on two different durations.

1) Contact duration of the transmitter and receiver, i.e., ϕ_1.
2) Idle duration of the channel, i.e., ϕ_2.

More specifically, the successful utilization relies on how long nonzero ϕ_1 and ϕ_2 coexist at the same time. Let us consider that ϕ_1 and ϕ_2 coexist during a time interval, i.e., θ, which is called the *feasible channel utilization interval*. For a given θ, BFC allows transmitter nodes to utilize any vacant channel by a *successful channel utilization probability* derived by the following theorem.

Theorem 1: Assuming that n_{ic} and ω_c $\forall i$, c is characterized by the normal random variables $\mathbf{n} \sim \mathcal{N}(\mu_n, \sigma_n^2)$ and $\boldsymbol{\omega} \sim \mathcal{N}(\mu_\omega, \sigma_\omega^2)$, respectively; the successful channel utilization probability of BFC, i.e., β, can be approximated as

$$\beta \cong \int_{-\infty}^{\vartheta} \Phi(s)\, ds \tag{20}$$

where $\Phi(s)$ is the standard normal density function and ϑ is given as

$$\vartheta = \frac{\frac{(\theta - m)(\omega_{\max}\mu_n - n_{\min}\mu_\omega) - \omega_{\max}\mu_n m}{\sigma_n \omega_{\max} m}}{\sqrt{1 + \left(\frac{(\theta - m)\sqrt{\omega_{\max}^2 \sigma_n^2 - n_{\min}^2 \sigma_\omega^2}}{\sigma_n \omega_{\max} m}\right)^2}}. \tag{21}$$

Proof: To ensure that any idle licensed channel can be always successfully used by an IMCRN node, the feasible channel utilization interval θ must be higher than the sum of the delay bound τ_u and the message duration m, i.e.,

$$\begin{aligned} \tau_u + m &< \theta \\ \frac{\omega_{\max} n_{ic} m}{\omega_{\max} n_{ic} - \omega_c n_{\min}} + m &< \theta. \end{aligned} \tag{22}$$

Based on $\mathbf{n} \sim \mathcal{N}(\mu_n, \sigma_n^2)$ and $\boldsymbol{\omega} \sim \mathcal{N}(\mu_\omega, \sigma_\omega^2)$, (22) can be modified as

$$\frac{\omega_{\max} \mathbf{n} m}{\omega_{\max} \mathbf{n} - \boldsymbol{\omega} n_{\min}} < \theta - m. \tag{23}$$

Since $\omega_{\max}$ and $n_{\min}$ are assumed to be constant and the linear operations over normal random variables also produce normal random variables, (23) can be also expressed as

$$\frac{x}{y} < \theta - m \tag{24}$$

where $x \sim \mathcal{N}(\mu_x, \sigma_x^2)$ and $y \sim \mathcal{N}(\mu_y, \sigma_y^2)$, and

$$\begin{aligned} \mu_x &= \omega_{\max}\mu_n m, \quad \sigma_x^2 = (\sigma_n \omega_{\max} m)^2 \\ \mu_y &= \omega_{\max}\mu_n - n_{\min}\mu_\omega, \quad \sigma_y^2 = \omega_{\max}^2 \sigma_n^2 - n_{\min}^2 \sigma_\omega^2. \end{aligned} \tag{25}$$

By standardizing the normal random variables x and y, (24) can be also written as

$$\frac{z_x + \frac{\mu_x}{\sigma_x}}{z_y + \frac{\mu_y}{\sigma_y}} < \frac{\sigma_y(\theta - m)}{\sigma_x} \tag{26}$$

[3]Here, each node is assumed to sense available channels by using an energy-based spectrum sensing mechanism [11].

[4]Note that the estimation of the interference level is out of the scope of this paper.

where z_x and z_y are the standard normal random variables, i.e., $z_x \sim \mathcal{N}(0,1)$ and $z_y \sim \mathcal{N}(0,1)$. Consequently, if (26) is satisfied, it can be ensured that any idle licensed channel can be successfully used by an IMCRN node. The probability that (26) is satisfied, i.e., β, can be also approximated as [14]

$$\beta = Pr\left(\frac{z_x + \frac{\mu_x}{\sigma_x}}{z_y + \frac{\mu_y}{\sigma_y}} < \frac{\sigma_y(\theta - m)}{\sigma_x}\right) \cong \int_{-\infty}^{\vartheta} \Phi(s)\, ds \quad (27)$$

where ϑ can be given as

$$\vartheta = \frac{\frac{\mu_y(\theta-m)-\mu_x}{\sigma_x}}{\sqrt{1+\left(\frac{\sigma_y(\theta-m)}{\sigma_x}\right)^2}}. \quad (28)$$

By substituting μ_x, σ_x, μ_y, and σ_y into (28), ϑ can be also rewritten as given in (21). The aim of the successful channel utilization probability β is to quantify the performance of the BFC algorithm. It is just a probability that an available channel is always utilized by a secondary user within a given time duration. Therefore, it tries to reflect the performance of the BFC algorithm in terms of channel utilization. Note that since the feasible channel utilization duration θ includes the average contact duration of nodes, β also takes the node contact durations into account. ■

V. Performance Evaluation

Here, we present the performance evaluation of the BFC algorithm. The simulation environment is created using MATLAB. We consider a generic mobility and spectrum availability model. The model assumes that any two nodes are contacted and able to communicate with each other using an available licensed channel with the probability p_x. The probability p_x is also assumed to be uniformly distributed over the interval $(0, p_u]$. p_u implicitly characterizes the dynamics of node contact statistics and heaviness of primary-user activities. In fact, many popular mobility models, such as random direction, random waypoint, and community-based mobility, follow similar models. Throughout this section, the end-to-end message delay is given in number of time intervals I used in the utility update, as introduced in Section II, and node energy values are scaled to the interval [0, 1]. We first present the results on the relay selection performance of BFC, and then, the channel selection performance is given.

A. Relay Selection Performance

In Fig. 1, the end-to-end delay provided by BFC is shown with varying p_u values according to the different numbers of nodes in the network, i.e., N. As p_u increases, the average of p_x selected from $0 < p_x \le p_u$ increases, which reduces the end-to-end message delay. However, the message delay slightly decreases with N. This is observed more apparently as p_u is relatively small, i.e., less than 0.05. Hence, it can be easily concluded that BFC can successfully utilize all contact opportunities regardless of the number of nodes in the network because it provides nearly the same end-to-end performance even if N changes from 25 to 75. In Fig. 2, the total energy consumption of network nodes in message delivery is shown for the same setting in Fig. 1. For a fixed N, the total energy consumption hardly increases, whereas end-to-end latency significantly reduces, as shown in Fig. 1. This reveals that BFC can always select the most appropriate relay nodes that can minimize the energy consumption. For example, for $N = 25$, end-to-end latency can be decreased from nearly 100 to 10. On the other hand, the total energy consumption only increases for nearly 0.35 to 0.43. This reveals that BFC can always follow the changes in the network and regulate its strategy to provide acceptable latency with minimum energy consumption. In Fig. 3, for the same scenario evaluated in Figs. 1 and 2, the number of relay nodes that are employed for the message delivery is shown with varying p_u values for the different values of N. The number of relay nodes increases with p_u. However, as observed in Fig. 2, the total energy consumption slightly changes, although the number of employed relays increases by nearly 350%. Hence, it can be easily inferred that BFC can always decide the relay nodes that minimize the total energy consumption. Furthermore, as p_u increases, BFC can adaptively track the changes in p_u and decrease the end-to-end latency by

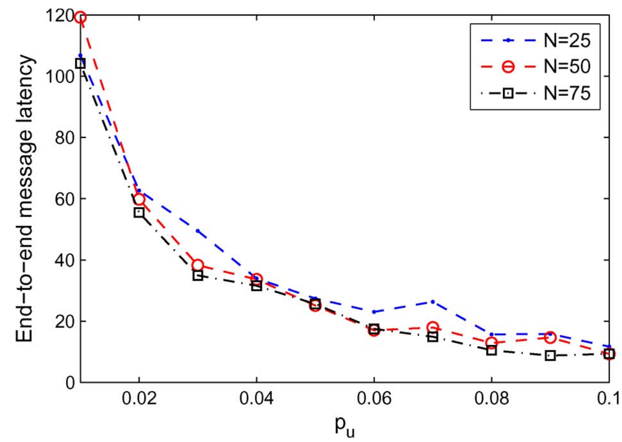

Fig. 1. End-to-end delay is shown with varying upper bounds of encounter probability, i.e., p_u, for different numbers of nodes N.

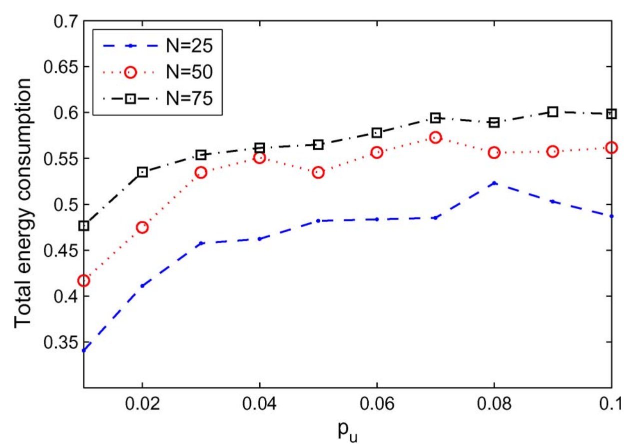

Fig. 2. Total energy consumption of nodes in message delivery is shown with varying upper bounds of encounter probability, i.e., p_u, for different N.

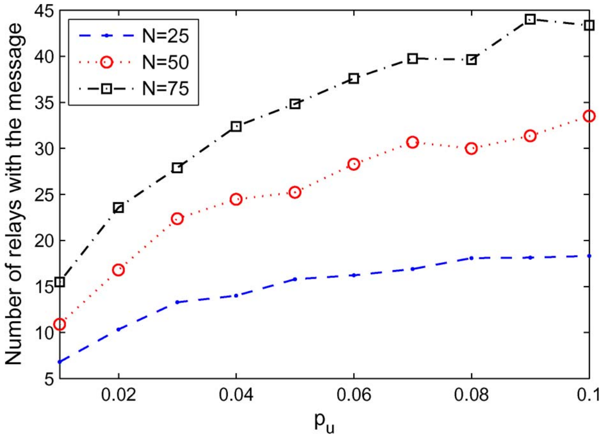

Fig. 3. Number of relay nodes that are selected by BFC is shown with p_u according to different N values.

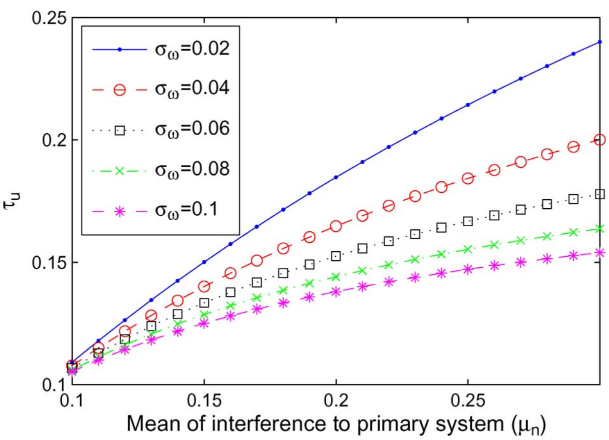

Fig. 4. Upper bound of channel allocation time τ_u is shown with varying μ_n values for different values of σ_ω.

increasing the number of relays, although it keeps the energy consumption in almost the same level.

B. Channel Selection Performance

Here, the channel selection performance of BFC is presented to understand how BFC enables IMCRN nodes to efficiently utilize the available spectrum channels. We give the performance results on the upper bound of channel allocation time, i.e., τ_u, given in (15). Interference level $\mathbf{n}$ and channel bandwidths $\boldsymbol{\omega}$ are assumed to be normal random variables, i.e., $\mathbf{n} \sim \mathcal{N}(\mu_n, \sigma_n^2)$ and $\boldsymbol{\omega} \sim \mathcal{N}(\mu_\omega, \sigma_\omega^2)$. Since 99.7% of values drawn from a normal distribution are within three standard deviations, $n_{\min}$ and $\omega_{\max}$ can be given as $n_{\min} \approx \mu_n - 3\sigma_n$ and $\omega_{\max} \approx \mu_\omega + 3\sigma_\omega$. Note that, throughout the evaluations, all of the parameters μ_n, σ_n, μ_ω, and σ_ω are scaled to the interval [0, 1].

In Fig. 4, the upper bound τ_u of the channel allocation time is shown with varying values of μ_n for different σ_ω values. The upper bound τ_u increases with μ_n. This helps the nodes that impose a higher level of interference on some channels to access these channels later than the other nodes. Hence, BFC mitigates interference along the network by delaying the accesses of the nodes that cause high interference. Furthermore, τ_u can be reduced as the standard deviation σ_ω of the channel bandwidth increases. This is because diversity of the channel bandwidths can be improved with σ_ω, and as σ_ω increases, the zero-one rule in (14) selects various channels more rapidly. Thus, BFC improves the performance as the diversity of these channels increases.

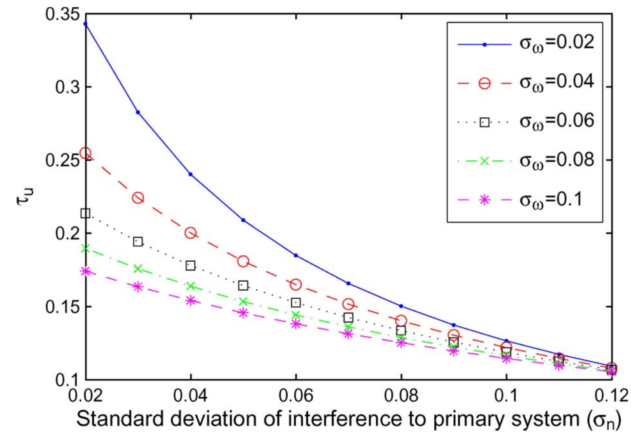

Fig. 5. Upper bound of channel allocation time τ_u is shown with varying σ_n values for different σ_ω values.

TABLE I
SUCCESSFUL CHANNEL UTILIZATION PROBABILILITY β ACCORDING TO VARYING m AND σ_n

m	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**
$\sigma_n = 0.1$	0.999	0.999	0.998	0.989	0.943	0.829	0.664
$\sigma_n = 0.15$	0.999	0.997	0.989	0.963	0.895	0.777	0.634
$\sigma_n = 0.2$	0.996	0.991	0.978	0.941	0.864	0.748	0.618

In Fig. 5, τ_u is shown with the standard deviation σ_n of interference for varying values of σ_ω. τ_u can be decreased by increasing σ_n. In fact, as σ_n increases, the number of nodes, which can easily find various licensed channel opportunities without interfering the primary system, increases. This reveals that BFC can potentially convert the various network conditions into a performance improvement.

In Table I, the successful channel utilization probability, i.e., β, is presented with varying message duration values, i.e., m, that are changed from $m = 0.03$ to $m = 0.09$, whereas the feasible channel utilization interval is $\theta = 0.1$. β is very close to 1 for $m = 0.03{-}0.06$. This means that, for these message duration values, BFC provides almost 100% spectrum utilization. As m is further increased up to $m = 0.09$, β is still relatively high, although m is very close to the feasible channel utilization interval, i.e., $\theta = 0.1$.

Similar to Table I, in Table II, it can be observed that BFC provides nearly 100% spectrum utilization when the message

TABLE II
SUCCESSFUL CHANNEL UTILIZATION PROBABILILITY β ACCORDING TO VARYING m AND σ_ω

m	0.03	0.04	0.05	0.06	0.07	0.08	0.09
$\sigma_\omega = 0.1$	0.998	0.995	0.986	0.955	0.883	0.765	0.627
$\sigma_\omega = 0.15$	0.998	0.996	0.988	0.960	0.890	0.771	0.631
$\sigma_\omega = 0.2$	0.999	0.997	0.989	0.963	0.895	0.777	0.634

TABLE III
SUCCESSFUL CHANNEL UTILIZATION PROBABILILITY β FOR VARYING m AND θ

m	0.2	0.3	0.4	0.5	0.6	0.7	0.8
$\theta = 0.9$	0.995	0.979	0.928	0.820	0.682	0.572	0.512
$\theta = 0.8$	0.994	0.974	0.907	0.774	0.631	0.537	—
$\theta = 0.7$	0.993	0.965	0.869	0.706	0.569	—	—
$\theta = 0.6$	0.991	0.946	0.797	0.612	—	—	—
$\theta = 0.5$	0.987	0.895	0.674	—	—	—	—

duration is appropriately selected. Note that BFC also produces almost 80% spectrum utilization, although the message duration is very close to the feasible channel utilization interval such that $m = 0.08$, whereas $\theta = 0.1$.

Finally, in Table III, β is presented for varying values of m with different θ values. Here, the results are taken by always setting m to less than θ. Therefore, some of the boxes in Table III remain empty. As observed, BFC provides a significantly high spectrum utilization even if the message duration is selected in close proximity of the feasible channel utilization interval.

VI. CONCLUSION

In this paper, based on a prey model in foraging theory, a BFC protocol has been introduced for IMCRNs. Using a foraging-inspired RSP measure, BFC allows each node with a message to decide whether to copy the message to a relay node by optimizing the tradeoff between its transmission effort and utility in message delivery. This mechanism eventually controls the total number of relay nodes used in message delivery to provide a sufficient level of message delay. Using a CSP measure, BFC also provides nearly 100% spectrum utilization while it minimizes the interference level to the primary system. BFC is a fully autonomous protocol. Without need for any *a priori* information or regulation, it enables network nodes to adaptively regulate their communication strategies according to a dynamically changing network environment.

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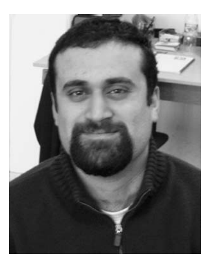

Baris Atakan (M'09) received the B.Sc. degree from Ankara University, Ankara, Turkey; the M.Sc. degree from Middle East Technical University, Ankara, and the Ph.D. degree from Koç University, Istanbul, Turkey, in 2000, 2005, and 2011, respectively, all in electrical and electronics engineering.

He is currently a Postdoctoral Research Fellow with the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, under the supervision of Prof. Dr. I. F. Akyildiz. His current research interests include nanoscale and molecular communication, nanonetworks, and biologically inspired communication for wireless networks.

Ozgur B. Akan (M'00–SM'07) received the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, in 2004.

He is currently a Full Professor with the Department of Electrical and Electronics Engineering and the Director of the Next-Generation and Wireless Communications Laboratory, Koç University, Istanbul, Turkey. His current research interests include wireless communications, nanoscale and molecular communications, and information theory.

Dr. Akan is currently the General Cochair of Association for Computing Machinery MOBICOM 2012 and IEEE MoNaCom 2012. He is also the Technical Program Committee Cochair of IEEE ISCC 2012. He is an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the *International Journal of Communication Systems* (Wiley), and the *Nano Communication Networks Journal* (Elsevier).