Survey of Bio-Inspired Resource Allocation Algorithms and MAC Protocol Design Based on a Bio-Inspired Algorithm for Mobile Ad Hoc Networks

Ji-Young Jung, Hyun-Ho Choi, and Jung-Ryun Lee

ABSTRACT

A variety of recent studies have attempted to apply biologically inspired (bio-inspired) algorithms to distributed resource allocation problems because they promise to enable efficient decentralized communication. In this article, we discuss the key challenges of MANETs with respect to bandwidth utilization, fairness, scalability, QoS, energy efficiency, and mobility. We also provide an overview of the state of the art of bio-inspired algorithms for resource allocation and describe the key benefits of using bio-inspired resource allocation algorithms in order to solve the various challenges of MANETs. Using the underlying key features of such bio-inspired algorithms, we design and implement a framework for a bio-inspired MAC protocol suited to MANETs and evaluate its performance. A simulation verifies that the proposed MAC protocol outperforms the existing MAC protocols in terms of throughput, delay, fairness, overhead, and energy efficiency. Finally, we discuss open issues associated with application of bio-inspired algorithms to resource allocation in MANETs.

INTRODUCTION

Mobile ad hoc networks (MANETs) are wireless networks in which mobile nodes (MNs) communicate with each other using multihop links without any centralized coordinator. Therefore, MNs are needed to access the communication medium in a distributed way, and the necessity of *distributed* medium access control (MAC) is emphasized. Under such a protocol, in general, contention increases as the density of nodes increases. Specifically, collisions increase due to the hidden node problem, which occurs when two nodes at a two-hop distance do not know of each other's existence and try to access the shared medium simultaneously. Bandwidth utilization efficiency is lowered because of the exposed node problem, which occurs when the exposed node detects that its neighbor is sending a packet to another node, senses the medium as busy, and therefore does not try to access the medium despite the availability of communication with its intended receiver [1]. The network topology in MANETs is highly dynamic, because wireless links are very vulnerable due to path loss, fading, interference, and mobility of the MN. Moreover, packet loss and delays accumulate whenever a packet is sent over a wireless multihop link, making it difficult to ensure a satisfactory end-to-end quality of service (QoS). These problems make it difficult to develop a stable and efficient algorithm for allocating resources in MANETs.

Recently, a number of studies were conducted with the goal of applying *biologically inspired* (bio-inspired) algorithms to a variety of engineering challenges. Bio-inspired algorithms are modeled on the behavior of organisms on Earth, which have evolved with the goal of achieving given purposes and ultimately obtaining optimal results by encapsulating simple, heuristic rules for operation in a distributed way. As we can observe from previous successful attempts at developing bio-inspired algorithms that have been reported in the literature [2, 3], they have excellent characteristics, such as convergence, scalability, adaptability, and stability. Drawing on these findings, a MAC protocol based on bio-inspired algorithms is expected to be able to cope with MANETs, in which network topology changes dynamically, a great number of nodes exist, and available resources are limited.

The authors discuss the key challenges of MANETs with respect to bandwidth utilization, fairness, scalability, QoS, energy efficiency, and mobility. They also provide an overview of the state of the art of bio-inspired algorithms for resource allocation and describe the key benefits of using bio-inspired resource allocation algorithms in order to solve the various challenges of MANETs.

CHALLENGES OF DEVELOPING A MAC PROTOCOL IN MANET

MAC protocols in MANET are classified according to channel access methods and fall into two categories: contention-based and scheduling-based protocols (CBPs and SBPs, respectively). In CBPs, MNs share a common medium to transmit data, so transmission collisions can occur when two or more MNs attempt to transmit simultaneously. Thus, the MNs try to avoid collisions by transmitting *opportunistically*, which means that although the MNs are ready to transmit data, they transmit it with a particular probability or after an extra random backoff period introduced to reduce the likelihood of collision. The most typical example of a CBP is carrier sense multiple access with col-

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Challenges	CBPs	SBPs
Bandwidth utilization	Bandwidth utilization decreases because of collisions among hidden nodes and unused bandwidth due to exposed nodes.	Bandwidth utilization decreases because of the high signaling overhead necessary to detect a two-hop neighbor's presence and time synchronization.
Fairness	It is difficult to ensure fairness since the MNs allocate resources opportunistically.	SBPs operating in fully connected networks can guarantee fairness via the elected coordinator among the MNs. However, in a purely distributed system, no centralized coordinator exists, and therefore it is difficult to ensure fairness.
Scalability	It is difficult to ensure scalability since the number of collisions increases significantly as the traffic load increases.	It is possible to ensure scalability because resources are reassigned without collisions among MNs via the exchange of control information whenever the traffic load and node mobility increase. However, this leads to an increase in control overhead.
QoS guarantee	The number of collisions usually increases with the number of hops due to an increase in the number of access attempts and the amount of interference. Eventually, the QoS deteriorates.	There are no collisions during data transmission, so guaranteeing QoS is easier. However, the number of guaranteed QoS users decreases because there is no multiplexing gain for resource allocation in SBPs.
Energy efficiency	Because of the absence of infrastructure and a constantly changing network topology, packet collisions during medium access are more likely. This results in wasted energy due to retransmission of corrupt packets.	In SBPs, a major cause of energy waste is high signaling overhead in the resource reservation procedure used to recognize a two-hop neighbor's presence and solve hidden/exposed node problems.
Mobility	Mobility can increase the incidence of packet collisions due to the hidden node problem, and decrease the rate of bandwidth utilization due to the exposed node problem.	The pre-allocated resources and information about neighbors may no longer be useful after the MN has moved, which can result in schedule inconsistencies.

Table 1. Challenges of developing a MAC with respect to CBPs and SBPs.

lision avoidance (CSMA/CA). In SBPs, the MNs transmit data by using pre-allocated resources, so there are no access collisions. SBPs are categorized according to the type of protocol for allocating resources, which principally comprise time-division multiple access (TDMA), frequency-division multiple access (FDMA), code-division multiple access (CDMA), and orthogonal frequency-division multiple access (OFDMA).

Given the harsh communication environment for MANETs, MAC protocols have to be designed carefully to cope with various challenges, such as bandwidth utilization, fairness, scalability, QoS guarantee, energy efficiency, and mobility. We describe these challenges with respect to CBPs and SBPs in Table 1.

As shown in Table 1, an SBP is more suitable for ensuring scalability and QoS in MANETs. However, CDMA, OFDMA, and FDMA protocols are unsuitable for MANETs because CDMA and OFDMA require high complexity in encoding and decoding messages, and FDMA is expensive because of the necessity of implementing bandpass filters. The TDMA protocol is the simplest and does not require special hardware unlike other SBPs, so it is appropriate for use in MNs with limited computing power. For this reason, we investigate only scheduling-based bio-inspired resource allocation algorithms with TDMA structure.

BIO-INSPIRED RESOURCE ALLOCATION ALGORITHMS

In recent years, various bio-inspired algorithms have been applied to the design of resource allocation algorithms in various network environments. In this section, we introduce six representative bio-inspired resource allocation algorithms: desynchronization (DESYNC), pulse-coupled-oscillator-based desynchronization (PCO-D), anti-phase synchronization (APS), optimal foraging theory (OFT), particle swarm optimization (PSO), and genetic algorithm (GA). These are described in Fig. 1 in view of natural phenomena and the corresponding bio-inspired model, and can be classified, as shown in Table 2, according to the taxonomies of the biological fields from which it was inspired [4] and the answers to the three questions [5]:

DESYNC: The logical opposite of firefly synchronization, inspired by the synchronized flashing of thousands of fireflies, is shown in Fig. 1a [6]. Rather than having nodes attempt to perform tasks at the same time, the algorithm has them perform their tasks at as great a temporal distance from each other as possible. It is assumed that nodes are aligned in ascending order of phase, and movement is around the ring in the clockwise direction from 0 to 1. When the phase of a node reaches 1, the node fires, or broadcasts, to indicate the termination of its cycle to its neighbors and resets its phase to 0. Each node records two reference phases: the one that precedes its own-phase (i.e., previous phase) and the one that occurs just afterward (i.e., next phase). When the next node fires, the node calculates the midpoint of its two reference phases (0 and 0.4) and jumps its phase toward the midpoint (0.2), as shown in Fig. 1a. Through iteration of this algorithm in each node, all of the phases are spaced evenly around the phase ring. Each node occupies the TDMA slots beginning at the midpoint between the previous phase and its own phase, ending at the midpoint between its own phase and the next phase. Thus, all of the nodes occupy the non-overlapping time slots evenly.

PCO-D: PCO synchronization is modeled after the operation of pacemaker cells, which are responsible for regulating the beat of the human heart, as shown in Fig. 1b [7]. PCO-D is based on the inverse of the phenomenon of the PCO synchronization process [8]. In DESYNC, each node jumps its phase to the midpoint of its two refer-

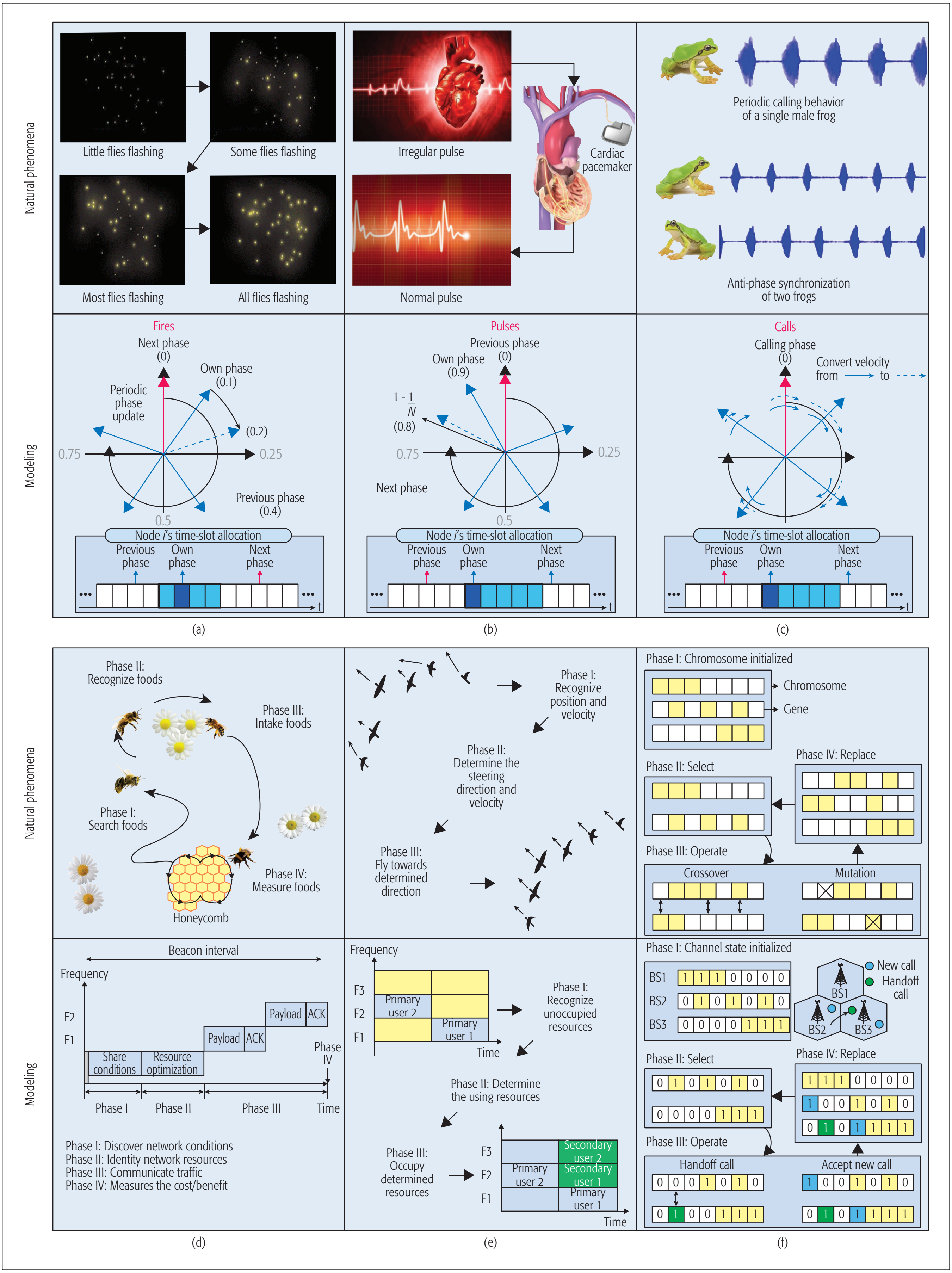

Figure 1. Illustration of six representative bio-inspired algorithms in view of natural phenomena and the corresponding bio-inspired model: a) DESYNC; b) PCO-D; c) APS; d) OFT; e) PSO; f) GA.

Given the harsh communication environment for MANETs, MAC protocols have to be designed carefully to cope with various challenges, such as bandwidth utilization, fairness, scalability, QoS guarantee, energy efficiency, and mobility.

Algorithm	DESYNC	PCO-D	APS	OFT	PSO	GA
Biological field	Self-organization					Evolution
What information is communicated?	Marker-based				Sematectonic	Marker-based
What is the flow of information?	Stagnant				Diffusion	
How is the information used?	Trigger-based			Follow-through		

* Marker-based: The information is obtained explicitly from other individuals.
* Sematectonic: The information is obtained implicitly from the current state of the environment.
* Stagnant: The information is stagnant within a specific environment.
* Diffusion: The information is diffused across the environment to a large number of individuals.
* Trigger-based: The reception of specific information triggers some actions by the individual.
* Follow-through: The information being communicated causes the individual to take some step-by-step action.

Table 2. Taxonomy of bio-inspired resource allocation algorithms.

ence phases when the next node fires. However, in PCO-D, the pulsing of a node pushes away all the nodes whose phases are in (1 – 1/**N**, 1) toward 1 – 1/**N** (0.8), as shown in Fig. 1b, where **N** is the number of nodes in a fully connected network. As a result, all of the phases are spaced evenly around the phase ring. Each node occupies the TDMA slots beginning at the point of its phase and ending just before the point of its next phase.

APS: Calls by male Japanese tree frogs (Hyla Japonica) are aimed at both attracting females and informing other males of their location. It is important that females are able to distinguish between two male frogs because each male seeks to mate with only one female. For this to occur, it is necessary for two or more interacting male frogs to call periodically, alternately, and with little overlap, as shown in Fig. 1c. APS is modeled after the calling behavior of these male frogs [9]. When a frog calls, all frogs except the calling frog change the angular velocity of the phase immediately to achieve a temporal distance from each other, as shown in Fig. 1c. Ultimately, all of the phases are spaced evenly around the phase ring, and each node occupies a TDMA slot, using the same method as PCO-D.

OFT: This is inspired by the way foraging individuals search cooperatively for food [10]. Any food item has both a cost incurred through the energy and time needed for searching and a benefit gained through the nutrients and energy by eating. Foraging individuals use the foraging phase cycle (FPC) model in order to maximize benefit while minimizing cost. For example, an individual (bee) searches for food (nectar) in a natural environment (phase I), recognizes the food state (phase II), consumes food abundant in nutrients (phase III), and measures the cost and benefit and shares information about the food (phase IV) in every cycle, as shown in Fig. 1d. The network FPC (NFPC) model is inspired by the biological FPC model and designed to gain distinct radio resources while minimizing signal-to-noise ratio (SNR), control message overhead, and communication energy overhead. Each node discovers the initial network conditions (phase I), identities network resources (phase II), communicates traffic using optimal resources (phase III), and measures the cost and benefit (phase IV) for every beacon interval, as shown in Fig. 1d. In this way, all the nodes occupy distinct radio resources.

PSO: This is nspired by the social behavior of flocking birds and schooling fish [11]. When a flock of birds fly, each bird flies within its region without colliding with others by following three simple rules that all display steering behavior: separation to avoid crowding neighbors, alignment with the average heading of its neighbors, and cohesion with the average position of its neighbors. Each bird recognizes the position and velocity of its neighbor (phase I), determines its steering direction and velocity (phase II), and flies without colliding with its neighbors (phase III), as shown in Fig. 1e. This swarming mechanism is enforced by letting every node allocate its resources in the time/frequency regions to avoid collision with other nodes. A PSO-based resource allocation scheme is proposed in order to allocate the unoccupied resources of primary users to secondary users while minimizing interference and collisions between the users in cognitive radio networks. Each secondary user recognizes the unoccupied resources of the primary users and the occupancy planning of the other secondary users (phase I), determines the resources to be occupied (phase II), and periodically occupies these resources (phase III), as shown in Fig. 1e. In this way, all the secondary users occupy resources without interference or collisions.

GA: This is inspired by the process of natural selection that belongs to the larger class of evolutionary algorithms [12]. In the GA, a chromosome with randomly generated genes is initialized (phase I). Each gene in the chromosome is selected to breed a new generation (phase II) and perform crossover and mutation (phase III). New generation genes (children), which are selected through genetic operations, replace the previous generation of genes (parents) (phase IV), as shown in Fig. 1f. A GA-based resource allocation scheme is proposed in order to minimize the blocking probability of new calls and the dropping probability of handoff requests, minimizing interference with the existing calls in cellular networks. Each gene represents a channel state that is on or off in a cell. In a cellular network, channel states in each cell are initialized by a base station (BS) (phase I), each channel is selected to admit a new or handoff call (phase II), and an acceptable call is admitted through an unused channel (phase III). New channel states replace the previous states (phase IV), as shown in Fig. 1f.

KEY BENEFITS USING BIO-INSPIRED RESOURCE ALLOCATION ALGORITHM IN MANETS

Simple and Heuristic Rules Increase Bandwidth Utilization: Bio-inspired algorithms evolve to achieve a given purpose and obtain an optimal result by following a set of simple and heuristic rules for operation without the aid of a central coordinator. These decentralized approaches can decrease the complexity of resource allocation; signaling overhead can also be reduced. Thus, bio-inspired resource allocation algorithms increase bandwidth utilization by reducing signaling overhead in MANETs.

Convergence Ensures Fairness: In some bio-inspired algorithms, each entity modifies its own event-generating behavior through mutual interactions. By repeating this procedure, the target metric for all nodes converge. This property of these algorithms ensures fair resource allocation in MANETs even when the network topology changes dynamically.

Self-Organization Ensures Scalability: Bio-inspired algorithms are modeled on the principles of living things that maintain ecosystems through autonomous and independent behavior. Self-organization technology is designed to achieve self-planning, self-configuration, self-management, self-optimization, and self-healing. In MANETs, this self-organization allows MNs to optimally plan and allocate available resources, and to autonomously manage and heal the network, which means that bio-inspired resource allocation algorithms ensure scalability.

Selecting the Good Fitness Value Would Improve QoS: In bio-inspired algorithms, each entity adjusts its behaviors (i.e., phase adjustment, finding routes to food, flying direction adjustment, and gene selection) by selecting the one with the best fitness value. Good choices probably have similar or better results, and, after a number of selections, the results will be good enough to solve the problem. In MANETs, this process allows the MN to select the optimal resources with shorter delay, lower cost, and less interference as much as possible.

Gaining the Most Benefit with Minimum Cost Would Increase Energy Efficiency: In bio-inspired algorithms, each entity tries to gain the maximum benefit at the minimum cost in order to achieve its goal. In MANETs, this characteristic allows MNs to occupy resources efficiently with low signaling overhead and complexity, so energy efficiency can be increased.

DESIGN OF A MULTIHOP DESYNC PROTOCOL

In MANETs, an MN can obtain network information such as signal-to-interference-plus-noise ratio (SINR), link state, and traffic load only by overhearing its neighbor's message; therefore, a marker-based algorithm is suitable. In addition, a stagnant flow is more suitable than diffusion, due to low overhead, and a trigger-based approach is necessary for MNs because the complexity of encoding and decoding messages in the trigger-based case is lower than that in the follow-through case. Thus, DESYNC, PCO-D, and APS are suitable for MANET, because they are marker-based, stagnant-flow-based, and trigger-based. In particular, DESYNC has been cited in many studies, and a number of follow-up studies were conducted to apply DESYNC algorithms to a variety of network environments, but not MANETs. On the other hand, an open issue needs to be addressed to make DESYNC practical for MANETs. In DESYNC, a node uses one of its data time slots (DTSs) to broadcast messages that inform its neighbors of its firing phase; its position in the sequence of entire DTSs implicitly identifies the firing phase of the node. Thus, a node cannot recognize the firing phases of two- or more-hop neighbor nodes. Moreover, firing collisions may occur when two-hop neighbors fire simultaneously at the same time slot. Now, we present a new bio-inspired MAC protocol called Multi-Hop DESYNC (MH-DESYNC) to guarantee fair scheduling between one- and two-hop neighbors, which extends previous DESYNC, to obtain fair resource allocation in not only fully connected networks but also mobile multihop networks.

FORMAT OF FRAME AND VIRTUAL FIRING MESSAGE

Figure 2 shows the frame and virtual firing message (VFM) structures and an example of resource allocation in MH-DESYNC. Each frame is divided into a control channel and a data channel. Each node broadcasts its VFM via the control time slot (CTS) in the control channel. A VFM consists of a preamble for time synchronization, CTS occupancy information, and information for the allocation of the virtual firing phase (VFP), which is used to allocate DTS. Information about CTS occupancy and VFP allocations is given by the node ID and hop count (I-H pair). The hop count is set to 0 and 1 to denote the node itself and one-hop neighbors, respectively. An I-H pair of CTS and VFP that is not assigned to any node is set to (0,0). Then the number of I-H pairs used to denote CTS occupancy information is denoted by C and is the same as the number of CTS in a control channel, so the location of an I-H pair denotes the location of CTS via which the corresponding node sends its VFM. The number of I-H pairs for VFP allocation is denoted by D and is the same as the number of DTS in a data channel.

THREE GOALS OF MH-DESYNC

Reliable Sharing of Firing Phase Information among One- and Two-Hop Neighbors: To prevent the hidden and exposed node problems, the firing phase information must be shared up to two-hop neighbors. In the MH-DESYNC algorithm, the firing phase of each node is shared among one- and two-hop neighbors explicitly by transmitting it in message form, which we call VFM. A control channel is defined in order to guarantee reliable transmission of the VFM. A VFM includes the VFP of both the node itself and its one-hop neighbors, so nodes that receive the VFM will identify the VFP of one- and two-hop neighbors. Reliable sharing of VFP makes stable data packet transmitting and receiving possible; therefore, MH-DESYNC can guarantee high bandwidth utilization and QoS. In addition, VFM can be transmitted without collision in each frame after the control channel is assigned. Thus, MH-DESYNC is more energy-efficient because it prevents frequent collisions of control packets in a high-traffic-load environment, thereby reducing the consumption of energy.

> Bio-inspired algorithms evolve to achieve a given purpose and obtain an optimal result by following a set of simple and heuristic rules for operation without the aid of a central coordinator. These decentralized approaches can decrease the complexity of resource allocation; signaling overhead can also be reduced.

We note that the performance degradation of MH-DESYNC owing to the mobility is the smallest among all of the compared schemes, because the frame-by-frame-based procedure enables nodes to quickly detect changes in their neighbors' information and to immediately detect network topology changes.

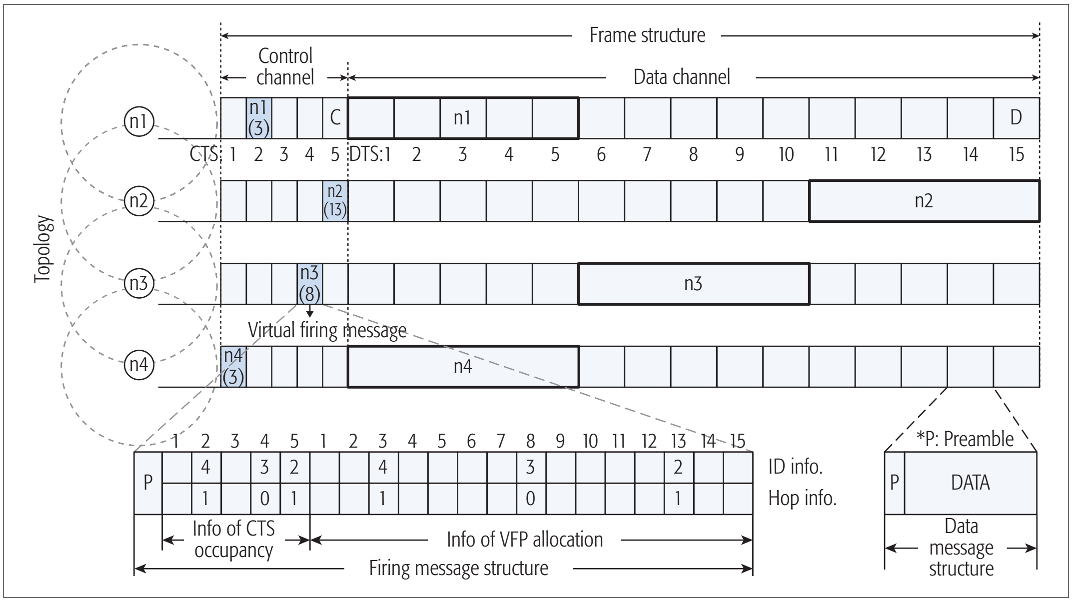

Figure 2. Frame and virtual firing message structures and an example of resource allocation in MH-DESYNC.

Adaptation to Network Topology Changes for Scalability: In MH-DESYNC, each MN occupies a time slot in the control channel i.e., CTS) at every frame and transmits its VFM via the occupied CTS.[1] This frame-by-frame-based procedure is expected to enable nodes to quickly achieve the changed neighbor information according to the movement of the MN and to detect changes in the network topology immediately, without additional exchange of control messages. Moreover, the reliable sharing of firing phase information containing ID and hop information among one- and two-hop neighbors enables nodes to recover the route in a short time. However, collisions may occur in respect to CTS occupancy when two-hop neighbors try to occupy the same CTS at the same time (i.e., CTS collisions). To avoid CTS collisions, the VFM of a node contains the CTS occupancy information of both the node itself and its one-hop neighbors, in addition to the VFP information.

Collision Detection/Resolution: Although CTS occupancy information in the VFM prevents CTS collisions among two-hop neighbors, collisions may still occur when multiple nodes joining the network simultaneously choose the same CTS. In this case, the neighbors of such nodes cannot update their CTS occupancy information. Thus, entering nodes receive VFMs from their neighbors, in which their CTS occupancy information is not updated and the CTS collision is identified. Then the node chooses a CTS again and repeats the procedure until the collision is resolved. Note also that firing phase collisions may occur when multiple nodes choose the same firing phase simultaneously. This problem is solved using a procedure structurally similar to that for detecting and resolving CTS collisions.

Operational Procedure of Resource Allocation in MH-DESYNC

Assuming the linear topology shown in Fig. 2, we explain the operational procedure of MH-DESYNC. When a node enters the network, it listens at consecutive frames and obtains information about CTS occupancy and VFP allocation from the VFMs of its neighbors. Then it chooses at random both a CTS not occupied by neighbors and its VFP not allocated to neighbors. Next, it composes its VFM using the CTS/VFP information obtained from its neighbors and broadcasts it via its chosen CTS. If there is no collision in CTS occupancy and VFP allocation, each node seeks the left/right nearest VFP and determines the left/right midpoint between its own and the left/right nearest VFP. The actual DTSs dedicated to the node's use are determined by the left and right midpoints. At the next frame, the node's VFP is updated toward the midpoint between the left/right nearest VFP, and the same procedure is repeated for DTS allocation.

Figure 2 shows the VFM for n3. If n3 broadcasts its VFM with the I-H pairs (4,1), (3,0), and (2,1) using the CTS/VFP information, n2 and n4 recognize the existence of each other as one-hop neighbors of n3. In this way, each node recognizes the exact CTS and VFP information for its one- and two-hop neighbors. Note that although n1 and n4 are allocated overlapping DTSs, their data transmissions do not collide, and these time slots are reused spatially because they are more than two hops away.

Performance Evaluation

The performance of MH-DESYNC is measured against those of the CSMA/CA and TDMA-based multi-channel MAC (TMMAC) [13], which are commonly used CBPs and SBPs in MANETs,[2] respectively. Table 3 presents the parameters used in the simulation runs.

Figure 3a–3c show the aggregate throughput, average delay, and fairness as functions of the packet generation interval and maximum speed of nodes. When the traffic load is low, the three MAC protocols achieve similar aggregated throughput, fairness, and stable average delay, because every node can acquire sufficient resources to send its packet; thus, the queuing delay is negligible. However, when the traffic load increases, MH-DESYNC and TMMAC achieve

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[1] Sharing of scheduling information among neighborhood nodes through periodic broadcasting of VFM is inspired by the periodic flashing of fireflies. This periodic message broadcasting significantly characterizes the bio-inspired MAC protocol compared to generic MAC protocols.

[2] The PCO and APS algorithms cannot be compared directly to the proposed MH-DESYNC because they operate only in fully connected networks.

Simulation factor	Value
Routing protocol	AODV
Network size	1,000 x 1,000 m2
Number of nodes	100
Number of source-destination pairs	15
Transmission rate	11 Mb/s
Transmission/carrier sensing range	250/500 m
Traffic model	CBR traffic
Packet generation interval	128/64/32/16/8/4 ms
Virtual firing-message size	316 bytes
RTS/CTS/ACK size	40/34/34 bytes
ATIM/ATIM-RES/ATIM/ACK size	83/83/83 bytes
Data packet size	512 bytes
Control channel length	20 ms
Data channel length	80 ms
ATIM window length	20 ms
Communication window length	80 ms
Random backoff count	5
Slot time/SIFS/DIFS/EIFS	20/10/50/85 ?s
CWmin	32
CWmax	1024
TX/RX/Idle/Sleep power	2.25/1.25/1.25/0.075 W
Mobility model	Maximum speed of nodes
Random Waypoint Model	1.4/10 m/s

Table 3. Simulation parameters.

higher aggregate throughput than CSMA/CA, because CSMA/CA wastes bandwidth due to backoff procedures and collision of control packets, while MH-DESYNC and TMMAC can avoid contention for data packets. Moreover, MH-DESYNC achieves the highest fairness and lowest average delay because MH-DESYNC makes every node acquire resources for every frame, while only the contention winner can acquire resources in TMMAC and CSMA/CA. As the mobility of nodes increases, the aggregate throughput and Jain's fairness index decrease due to the increased incidence of packet collisions and packet drops, and the average delay increases because the time taken for route recovery increases.

Figures 3d and 3e show signaling overhead and energy per bit as functions of the packet generation interval and maximum speed of nodes. In MH-DESYNC, each node uses only one VFM for resource allocation even though the size of a VFM is larger than that of other control messages, that is, request to send (RTS), clear to send (CTS), acknowledgment (ACK, used in CSMA/CA), ad hoc traffic indication map (ATIM), ATIM-reservation (ATIM-RES), and ATIM-acknowledgment (ATIM-ACK) (used in TMMAC). Thus, when the traffic load is low, CSMA/CA, which uses small control packets, achieves the lowest signaling overhead. However, when the network load is high, signaling overhead for MH-DESYNC is the lowest because, unlike CSMA, MH-DESYNC can avoid contention during control channel access. TMMAC, which inherently supports power-saving mode, has the highest energy efficiency. The energy efficiency of MH-DESYNC is similar to that of CSMA/CA when the packet generation interval is less than 8 ms. However, MH-DESYNC consumes less power than CSMA/CA when the packet generation interval is greater than or equal to 8 ms because power consumption for signaling in MH-DESYNC is lower than that for CSMA/CA. This is due to frequent control packet collision/retransmission in CSMA/CA in a high-traffic-load environment. As the mobility of nodes increases, the signaling overhead increases because of the increase in the number of total control packet bits due to the routing overhead, and also the energy per bit increases because of the decreasing total network throughput due to packet collisions and packet drops.

We note that the performance degradation of MH-DESYNC due to mobility is the smallest among all of the compared schemes, because the frame-by-frame-based procedure enables nodes to quickly detect changes in their neighbors' information and to immediately detect network topology changes.

Most bio-inspired resource allocation algorithms model the behavior of living entities assuming that they are awake. Therefore, the bio-inspired resource allocation algorithms do not inherently use power-saving modes and thus do not offer benefits for energy conservation.

OPEN ISSUES ASSOCIATED WITH APPLICATION OF BIO-INSPIRED ALGORITHMS TO RESOURCE ALLOCATION IN MANETS

Energy Efficiency: Most bio-inspired resource allocation algorithms model the behavior of living entities assuming that they are awake. Therefore, bio-inspired resource allocation algorithms do not inherently use power-saving modes and thus do not offer benefits for energy conservation, as verified in Fig. 3e. Thus, it is necessary to study a method of applying power-saving mode to bio-inspired resource allocation algorithms. However, power-saving mechanisms can cause additional signaling overhead associated with sleep scheduling. Thus, bio-inspired resource allocation algorithms equipped with power-saving modes should be carefully designed considering the trade-off between energy efficiency and signaling overhead.

Determination of Initial Values: When applying a bio-inspired algorithm to resource allocation in a MANET, performance can be affected by the initial value of each MN. For example, the frequency reuse rate may vary according to the initial VFP in MH-DESYNC. When MNs A and B are apart more than two hops, and there is no other MN's phase between their phases, the phases of the two MNs will overlap, as shown in Fig. 2, thereby increasing the frequency reuse rate. Otherwise, the frequency reuse rate will decrease. Another example of performance variation is the end-to-end delay of the routing path, which varies according to the initial position of the phase in MH-DESYNC. Suppose that there are two MNs, A

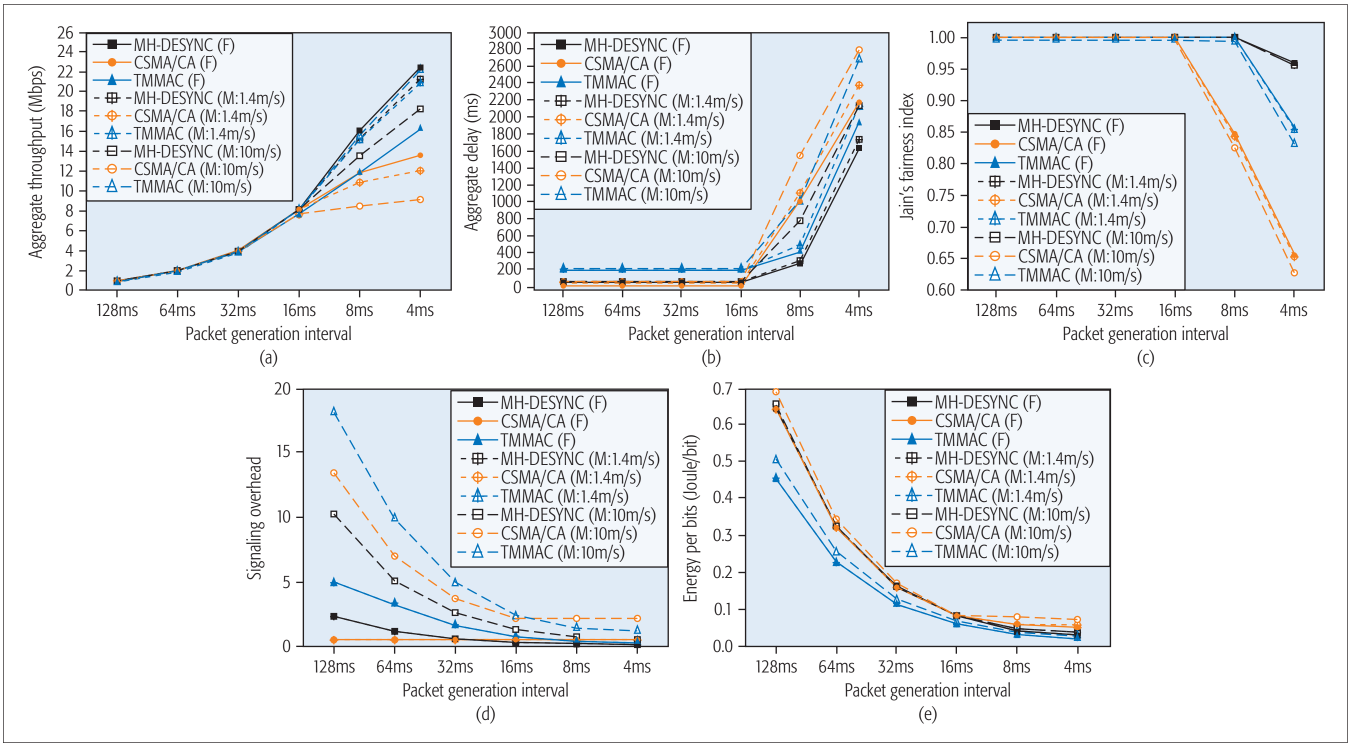

Figure 3. Performances of aggregate throughput, average delay, fairness, signaling overhead, and energy-per-bit (F: fixed network, M: mobile network when the maximum speed of nodes is 1.4 m/s or 10 m/s): a) aggregate throughput; b) average delay; c) Jain's fairness index; d) signaling overhead; e) energy per bit.

and B, on the route, and the order of VFP of MN A precedes that of MN B. Then packets sent from MN A can arrive at MN B during only one frame. However, if MN B sends a packet, it takes two frames, due to inversely allocated phases of MNs A and B. Thus, the initial value of each entity in bio-inspired resource allocation algorithms should be carefully designed by considering frequency reuse rate, end-to-end delay in a routing path, and so on.

Dynamic Bandwidth Allocation: In a distributed environment, the amount of resources reserved for an MN is determined by the external environments, such as the number of one- and two-hop neighbors contending with it. However, the amount of resources required for an MN may be different depending on the application's QoS requirements, transmission link status, and the number of connections passing through the MN. Thus, there is a need for further research on a mechanism that allows an MN to dynamically reserve the amount of bandwidth considering the various factors that affect the amount of resources required for the MN.

Prediction of Network Topology Changes: In bio-inspired resource allocation algorithms, reliable sharing of information about one- and two-hop neighbors enables MNs to exclusively occupy resources without collision. However, collisions still exist because MNs can join or leave the transmission radius of other MNs due to mobility. To mitigate these mobility-related collisions, it is necessary to predict network topology changes by sharing additional information about location, moving direction, and speed of more than two-hop neighbors by considering additional signaling overhead.

Analysis of Stability: In a distributed computing environment, it becomes very important to analyze convergence conditions and convergence speed to predict the results of operation of each entity and to confirm the stability of the system. In most bio-inspired algorithms, analysis of the system's stability remains at the conjecture level [6]; it is especially difficult to conduct stability analysis in a multihop environment. Therefore, the ability to analyze the stability of a bio-inspired resource allocation algorithm is an important issue to be studied for applying a bio-inspired algorithm to practical mobile multihop networks.

CONCLUSION

We have investigated the fundamental challenges in designing a MAC protocol for MANETs. Through the overview and key benefits of bio-inspired algorithms, we have shown that they can be used effectively when designing a distributed MAC protocol. However, because previous bio-inspired algorithms presupposed a fully connected network, they are not directly applicable in MANETs. We suggest MH-DESYNC, which resolves some practical issues such as the reliable sharing of two-hop neighbor information, being adaptive to changes in network topology, and avoiding possible collisions of signaling messages. Simulation results show that with increasing traffic load and increasing mobility, MH-DESYNC achieves the highest aggregate throughput with low control overhead and low rate of packet collisions compared to other competitive algorithms, which shows that MH-DESYNC exhibitsa high scalability compared to TMMAC and CSMA/CA. MH-DESYNC can also avoid redundant overhead caused by packet collision, achieving high throughput, high fairness, and short delays in a high-traffic network. We hope that this article presents a suggestive approach to a variety of readers who want to design a distributed MAC protocol for MANETs.

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