A Cell Biology Inspired Model for Managing Packet Broadcasts in Mobile Ad-hoc Networks

Sulochana J. Sooriyaarachchi*, Anil Fernando**, Chandana D. Gamage*
*Department of Computer Science and Engineering, University of Moratuwa, 10400, Sri Lanka
**Centre for Vision Speech and Signal Processing (CVSSP), Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH
sulochanas@cse.mrt.ac.lk, w.fernando@surrey.ac.uk, chandag@cse.mrt.ac.lk

***Abstract*—The modern computing paradigm is moving towards personal devices that incorporate wireless networking, mobility, and collaborative applications. The networking paradigm that best matches this scenario is the mobile ad-hoc network (MANET). A common instance of a MANET is the dense MANET that can be expected in any setting where large number of people congregate such as movie theatres, sports stadiums, shopping malls, transportation hubs, lobby of public offices, lecture rooms, etc. The existing packet transmission protocols for MANETs are inefficient for dense MANETs due to packet broadcast storms for stateless protocols and non-availability of anchor nodes for stateful protocols. This paper presents a new packet broadcast model developed based on cell biology and provides simulation results on protocol efficiency. As smart phone devices and collaborative applications proliferate among users, the proposed dense MANET protocol could provide real benefits to Internet enabled users and devices.**

***Index Terms*—Mobile ad-hoc networks, Packet broadcasts, Cellular automata.**

I. Introduction

THE current trend in day-to-day communication of average people is towards the intensive use of mobile devices such as smart phones and slate type computers. These devices are generally capable of connecting via cellular networks, WiFi or Bluetooth. The abundance of such portable communication devices with wireless capabilities gives rise to potential ubiquitous computing experiences. For example a traditional classroom can be converted into a collaborative learning environment via a stand-alone ad hoc network of mobile phones. Another application would be for friends roaming in a shopping mall to detect each other and share ideas using an on-the-fly ad hoc network without the support of cellular networking infrastructure or WiFi hotspots in the arena. In this research we focus on a dense network of such mobile devices that could be visualized as a dense Mobile Ad-hoc Network (dense MANET).

MANETs are generally dynamic in terms of topology thus making it challenging to device a routing mechanism. There is added complexity into routing when these MANETs are dense in nature. For example the routing tables maintained in mobile nodes with the existing routing schemes such as AODV, TORA and DSR will become unmanageably large in size and the network will get overloaded with flooded control packets. Therefore, it is essential that the nodes in a dense MANET keep less or no state information, specifically pertaining to global network and even the neighboring nodes. It is also important that the nodes send the least amount of control packets to conserve resources such as battery life. Due to the unavailability of a suitable routing mechanism the users have to rely on cellular networks without utilizing the powerful near-field communication technologies such as Bluetooth even when the devices are at line of sight.

Blind rebroadcasting is the simplest form of packet routing that allows the nodes to be stateless. Consequently, there is high probability that the intended destination will receive the packet. However, this scheme will cause broadcast storms, thus, resulting in severe degradation in performance, scalability and efficiency. Hence our aim is to find a mechanism to send a data packet from one node to another in a dense MANET while minimizing broadcast storms and leaving the nodes to be stateless. However, this is a difficult problem.

Biological inspirations have given promising results in arriving at satisfactory solutions for difficult problems similar to above, especially in communication networks. For instance Wedde et.al proposes an energy efficient routing algorithm known as BeeAdHoc for MANETs inspired by the foraging principles of honey bees to address the energy dilemma in MANETs [1]. Gunes et.al in [2] addresses the issue of packet overhead in routing and proposes Ant-Colony-Based Routing Algorithm (ARA) inspired by swarm intelligence in ant colonies. Similarly a number of studies base their solutions on ant colony optimizations [3], [4]. Moreover, Sarafijanovic and Boudec address the problem of node misbehavior in MANETs and gain inspirations from the human immune system for their solution [5]. Similarly, Kefalas et.al bases their solution for the problem of modeling dynamic behavior of multi-agent systems on the evolution of human tissues [6].

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S. J. Sooriyaarachchi is with the Department of Computer Science and Engineering, University of Moratuwa, 10400, Sri Lanka, (corresponding author, phone: +94112640380, fax: +94112650912, e-mail: sulochanas@cse.mrt.ac.lk)

W. A. C. Fernando is with the Centre for Vision Speech and Signal Processing (CVSSP), Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, (phone: +441483682353, fax: +441483686031, e-mail: w.fernando@surrey.ac.uk)

C. D. Gamage is also with the Department of Computer Science and Engineering, University of Moratuwa, 10400, Sri Lanka, (phone: +94112640380, fax: +94112650912, e-mail: chandag@cse.mrt.ac.lk)

There are biological systems that show similar characteristics of a dense MANET that tries to achieve a common task by cooperating among autonomous entities. An organ in human body for instance is also made out of a dense population of biological cells. These cells divide themselves repetitively in the process called *cell proliferation* and that is analogous to re-broadcasting of packets in a MANET. It is an interesting question to ask "On what basis our ears end up growing into a particular size?". The nature has its regulatory mechanisms for controlling the cell division in an organ. These biological regulatory mechanisms would inspire us in finding a mechanism to manage redundant broadcasts in a dense MANET with a simple rebroadcasting scheme.

II. Related Work

This section briefs the routing approaches available in the area of MANETs and how our approach differs.

A. Traditional Approaches

Traditional routing approaches proposed and implemented in MANETs are based on existing routing protocols of wired networks. Data communication networks originated with the intention of connecting fixed wired terminals. Need for routing mechanisms arose as a result of the growth of the networks by size and geographical spread. The networks started to support wireless nodes with the intension of using existing communication networked resources [7]. Hence, the wireless nodes always had the support of some kind of fixed infrastructure so that the then-existed wired routing protocols were tweaked and customized to support a few number of wireless nodes. Dedicated fixed infrastructure were implemented such as base stations in cellular networks and wireless access points in local area networks when the mobile nodes increased in number [8]. However, the concepts behind almost all routing protocols used in MANETs are hooked to fixed infrastructure at least by assuming few key nodes in the network to act as fixed and routing nodes. The most recent work in the area of MANETs is IEEE 802.11s which defines MANETs as Wireless Mesh Networks. Mesh Stations even in IEEE802.11s standard act as Access Points in infrastructure mode wireless networks thus managing routing and control [9]. We consider the routing paradigm that bases on fixed infrastructure and requires to maintain routes as the *fixed-stateful approach*.

However, the current trend in MANETs seeks a paradigm shift in approaching the problem of routing as various mobile devices emerge in large numbers and with powerful near-field wireless networking capabilities. In parallel the supporting technologies and concepts for ubiquitous computing and connectivity develop at a rapid phase. For example IPv6 allow a large population of mobile devices to connect in a single network, while WiFi and Bluetooth provide powerful near field communication. Hence we seek routing mechanisms that base on the other extreme in contrast to fixed-stateful paradigm in traditional MANET routing. So we dare to take the opposite of the traditional routing paradigm and bases our solution on the *mobile-stateless approach*.

B. Mobile-stateless Routing Paradigm

A comparison of our approach and the traditional approaches of MANET routing is summarized in figure 1. The simplest and stateless mechanism of sending a packet from one node to another in a MANET is blind-rebroadcasting. In this mechanism a node re-broadcasts each and every packet it receives, except for those destined to the node itself. However, it causes unnecessary amount of redundant rebroadcasts especially when the MANET is dense. Hence we base our solution on blind-rebroadcast and try to reduce redundant rebroadcasts using biologically inspired regulatory mechanisms. These regulations in turn requires us to maintain certain amount of states thus shifting our approach slightly towards stateful side. Consequently, our approach is placed at a position shown in figure 1 rather than at the mobile-stateless extreme. However, the states maintained in our approach does not gather global information from nodes network-wide as in traditional routing approaches. Information that our approach requires is of itself and immediate neighborhood along with those carried by the received data packets.

Although there are routing protocols proposed based on cell biological inspirations, such as in [10] they also base their solution on existing AODV-like protocols and maintain routing tables while not considering node densities. Cellular Automata based models are also found as in [11] and [12] for mobile networks but they are not in the scope of dense MANETs or related to routing as in our work.

C. Network wide Reach in MANETs

It is often essential that the packets should be sent to every node in a MANET, at least for house keeping tasks such as discovering routes and updating routing tables in traditional MANET routing. For example, AODV which is the most popular routing protocol in MANETs, relies on Sequence Number Controlled Flooding as the mechanism to send RREQ packets throughout the network [13]. IEEE802.11s also uses AODV as the routing protocol [14]. Hence flooding is a decisive aspect of MANETs. The initial idea for our work was intended to route data packets based on blind rebroadcasting or on flooding. However, the findings are applicable in enhancing the available routing protocols which rely on some kind of flooding to reach all nodes in a network. Hence this work can also be considered as a contribution to the improvement of flooding in MANETs.

III. Biological Inspirations

This section explains the biological inspirations for limiting the packet rebroadcasts in a MANET based on biological literature related to organ growth.

A. Limiting the Packet Growth inside the MANET

Our aim was to control the growth of the number of rebroadcasts of a data packet inside the MANET with the inspiration from the organ growth control by inhibition of cell proliferation. Since a human organ is generally made out of millions of cells it is an ideal system to mimic the dense

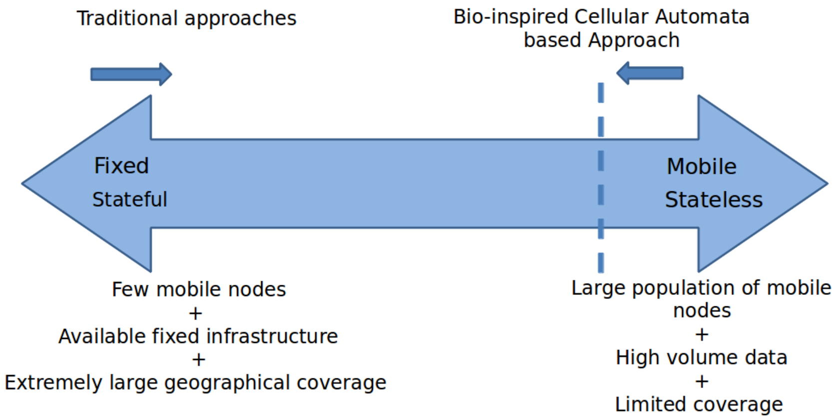

Fig. 1. Summary of comparison of our routing approach with reference to fixed-stateful and mobile-stateless routing paradigms

nature of the mobile network of our interest. Any regulatory mechanism that controls the cell proliferation in the growth of such organs would be a candidate biological inspiration to manage broadcast storms in the target network.

According to Lui and Baron [15], the human body has a growth deceleration mechanism driven at the physiological level by growth itself and at a molecular level by a cell intrinsic genetic program. This claim is supported by the authors in [16]. Lui and Baron in [15] further elaborate that the local communication mechanisms play the central role in growth deceleration rather than the systemic mechanism. Bryant and Simpson in [17] also highlight the evidence for organ intrinsic mechanisms in growth control in organs. However, the growth deceleration program is not cell autonomous but it depends on the interaction of the cell with the extra-cellular micro environment [15].

B. Using Growth as the Inhibitor of Growth

The genetic program explained in [15] is responsible for growth inhibition according to the inputs related to growth itself such as the number of accumulated cells, organ functionality and the number of cell divisions undergone. This genetic program up or down-regulates growth promoting genes according to a negative feedback loop. The hypothesis that the growth itself causes growth inhibition is also proved by Forcinito et.al in [18].

C. Terminal Conditions

According to the authors in [15] the Growth Program described above down-regulates the growth-promoting genes when (i) the accumulated number of cells reach the saturation level, (ii) the organ is adequately grown to perform the intended functionality or (iii) the number of divisions undergone is equal to the particular number set during the embryonic stage.

D. Growth Sensing Mechanisms

Individual cells sense the growth in terms of number of accumulated cells by means of the concentration of some secreted molecules known as *chalones* [15]. Bullough [19] coined the term chalone and hypothesized it as the inhibitors of cell growth by negative feedback to control the size of a tissue. A number of studies provide experimental evidence in support of this hypothesis [20], [21], [22], [23]. Growth in terms of the level of functionality is sensed for example in the liver by flux of bile acids. Bile acids are synthesized in liver and secreted into small intestine to facilitate digestion. Bile acid is then reabsorbed and returned to liver. The number of cell divisions undergone is measured using cell cycle counting mechanisms such as telomere shortening [15].

IV. Cell Biology Inspired Packet Transmission Model

Our work at the current stage is heavily inspired by the chalone method of growth inhibition in biological organ growth explained in section III-D. This section explains how we apply the chalone mechanism in order to limit the packet rebroadcasting in MANETs.

The number of packets in our MANET grows by rebroadcasts in analogy to the cells that proliferate by dividing themselves. Hence we map a data packet residing in a mobile node, to a biological cell in an organ. Also the packet rebroadcasting is mapped to biological cell division. Similar to the case that the biological cell has the growth-controlling-genetic program running inside itself the broadcast-controlling program runs in the mobile node that contains a packet. Table I summarizes the mapping from biological system to MANETs.

The chalone concentration sensed by a cell in its micro-environment represents the number of cells in the neighborhood in the biological system. Similarly we map chalone concentration to the number of neighbors who have already broadcast a particular data packet. We borrow the term *chalone* for the control packets that we introduce as cues for carrying information about the neighborhood in MANETs. Thereby we introduce a set of control packets that are never forwarded beyond the transmission range of a node. A node that receives a data packet obtains information in order to decide whether to rebroadcast the packet. The information requested is whether

TABLE I
SUMMARY OF MAPPING FROM BIOLOGICAL SYSTEM TO MANET

Biological System	MANET
Biological cell	Data packet in a node
Cell division	Packet rebroadcasting
Chalone	A control packet exchanged only with the neighbors. Neighbors are the nodes within the transmission range of a node.
Chalone concentration	Number of neighboring nodes who have already broadcast the Data Packet.
Chalone threshold	Threshold for the number of neighboring nodes who have already broadcast the Data Packet for rebroadcasting.
Organ maturity	The state that the Data Packet reached its destination.

the neighbors have already rebroadcast the particular data packet in hand. We name the control packet that does the above request as *chaloneInit* to denote the initiation of chalone mechanism. The control packet sent by neighbors in response to chaloneInit is named *Chalone* packet.

V. THEORETICAL MODEL

A. Operational Model based on Cellular Automata

Typically cell biological systems are modeled in terms of Cellular Automata as in [24], [25], [26], [27]. In analogy the biologically inspired MANET model is theoretically analyzed based on Cellular Automata in this section.

Cellular Automata (CA) are defined as mathematical idealization of problems or physical systems in which space and time are discrete and the physical values take on finite set of discrete values [28]. This was invented by John von Neumann in 1940s as a result of biological motivation with an intention to design self-replicating artificial systems. Power of CA lies in its fundamental properties that are also found in the physical world: CA are massively parallel, homogeneous and all interactions are local [29]. Therefore a variety of physical and biological systems have successfully been modeled and simulated using CA [30], [25], [31], [32], [33].

One-dimensional two-state CA is extensively elaborated in [28]. Formalism of CA is found in [34] for multi-dimensions which is an exhaustive algebraic treatment of the subject. The type of CA of our interest is two-dimensional as the nodes in the MANET lie effectively on a plane. Authors in [35] further analyze two-dimensional CA and cites [34] for *additive two-dimensional* CA. According to [35], a two-dimensional CA consists of a regular lattice of sites. Each site takes on k possible values. Each site is updated in discrete time steps according to a rule ϕ that depends on the values of sites in some neighborhood around it at the previous time step. Authors in [35] addresses the special class of ϕ known as *totalistic rules* in which the values of a site depends only on the sum of values of the neighbors.

Our CA model of MANET is also viewed as a regular lattice on which mobile nodes are randomly placed. Each site takes only two values: 1 - node has rebroadcast a specified data packet, 0 - otherwise. Neighborhood for our CA is the circular region captured by the radio range of a mobile node. Any node within the range will respond as a neighbor. We also apply totalistic rule in which we count the total number of neighbors who have rebroadcast a specified data packet. We set a threshold for this number so that a node decides to rebroadcast a received data packet only if the number of neighbors who have already rebroadcast the packet does not exceed the threshold. This threshold will be referred to as *chalone threshold* hereafter.

B. Graph based Evaluation Model

We also assess the reachability of our protocol against that of flooding. As our protocol suppresses broadcasts using a threshold value there is a possibility that the data packet may not be received by certain nodes in the network. However flooding will make sure that all nodes in an unpartitioned network will receive a broadcast message.

In order to assess reachability we model the MANET as a unit disk graph of the following manner: vertices are the mobile nodes and the edges denote the availability of a direct wireless link between nodes at a given point in time. We first take the Euclidean distance between every node pair and then determine the immediate neighborhood by considering the transmission ranges. It is analogous to superimposing the communication ranges of nodes on the physical location map of the network. The graph may also change as the nodes connect or disconnect due to mobility, user actions or power availability.

In order to evaluate reachability of the resulting graph, we use Floyd-Warshall algorithm for its simplicity, parallel computation for all node pairs, and less pre-processing needs. If a path can be found by the algorithm then we can conclude that a node can reach any other node by simple flooding.

VI. SIMULATION

We used OMNET++ 4.4 with inet-2.2.0 for our simulation. OMNET++ is an event-driven and modular simulation framework [36].

The simulation model under study comprises an array of hosts configured as nodes of a single private network. The number of nodes is specified as a parameter at runtime as directed by the omnetpp.ini configuration file. We identify a data packet uniquely by its source address and a sequence number which in combination referred to as *Packet ID* hereafter. The sequence number is assigned to a packet by the originator of that packet. A node maintains a list of Packet IDs it sees or it creates. It also keeps a list of neighbors who responds for a chaloneInit Message. When a node receives a data packet the flow of events occurs as given in figure 2.

On the receipt of a chaloneInit message the source node ignores it while the destination is supposed to initiate another type of negative feedback mechanism similar to mechanism (ii) given in section III-B. However, the feedback mechanism is not in the scope of this paper. Flooding is for the global broadcast in a MANET in typical routing mechanisms and the terminal condition is when a packet reaches all the nodes

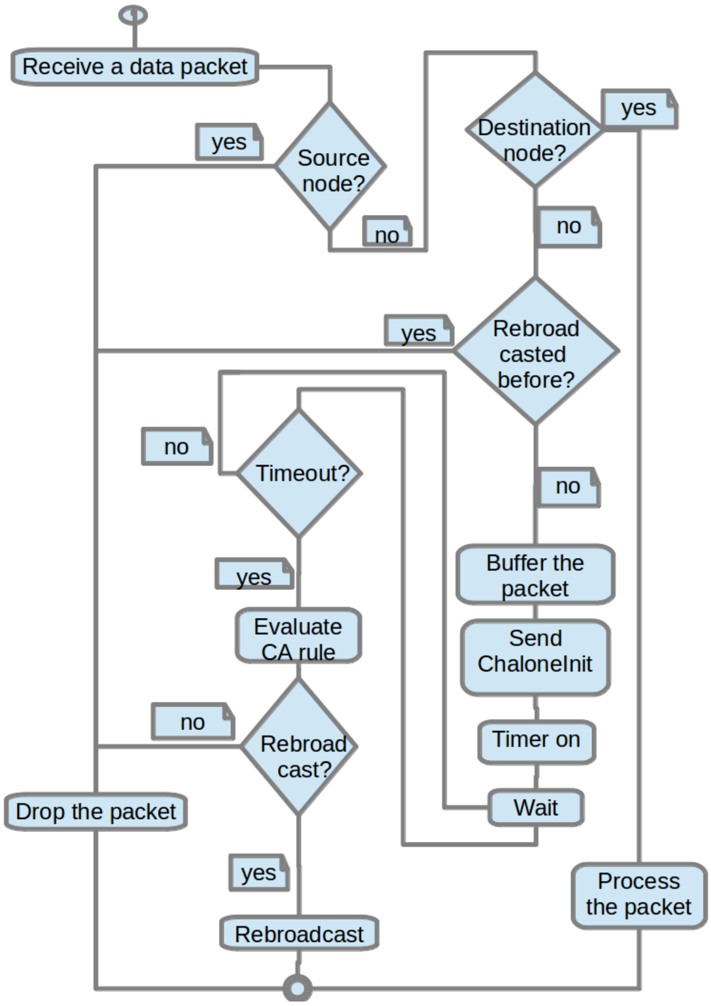

Fig. 2. Event flow at a receipt of a data packet by a node

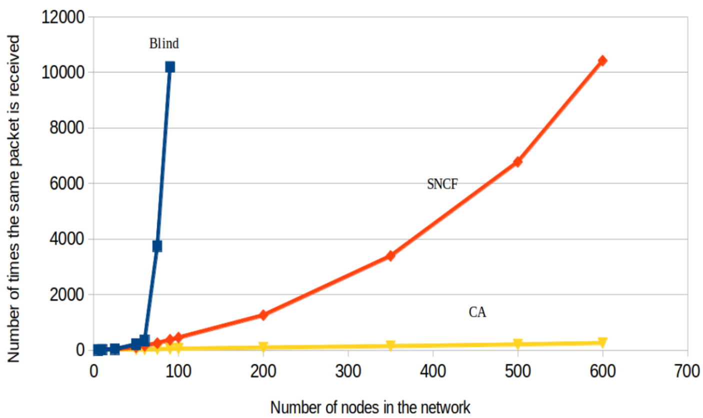

Fig. 3. Performance of Cellular Automata based Rebroadcasting (CA) protocol compared with Blind Rebroadcasting (Blind) and Sequence Number Controlled Flooding (SNCF)

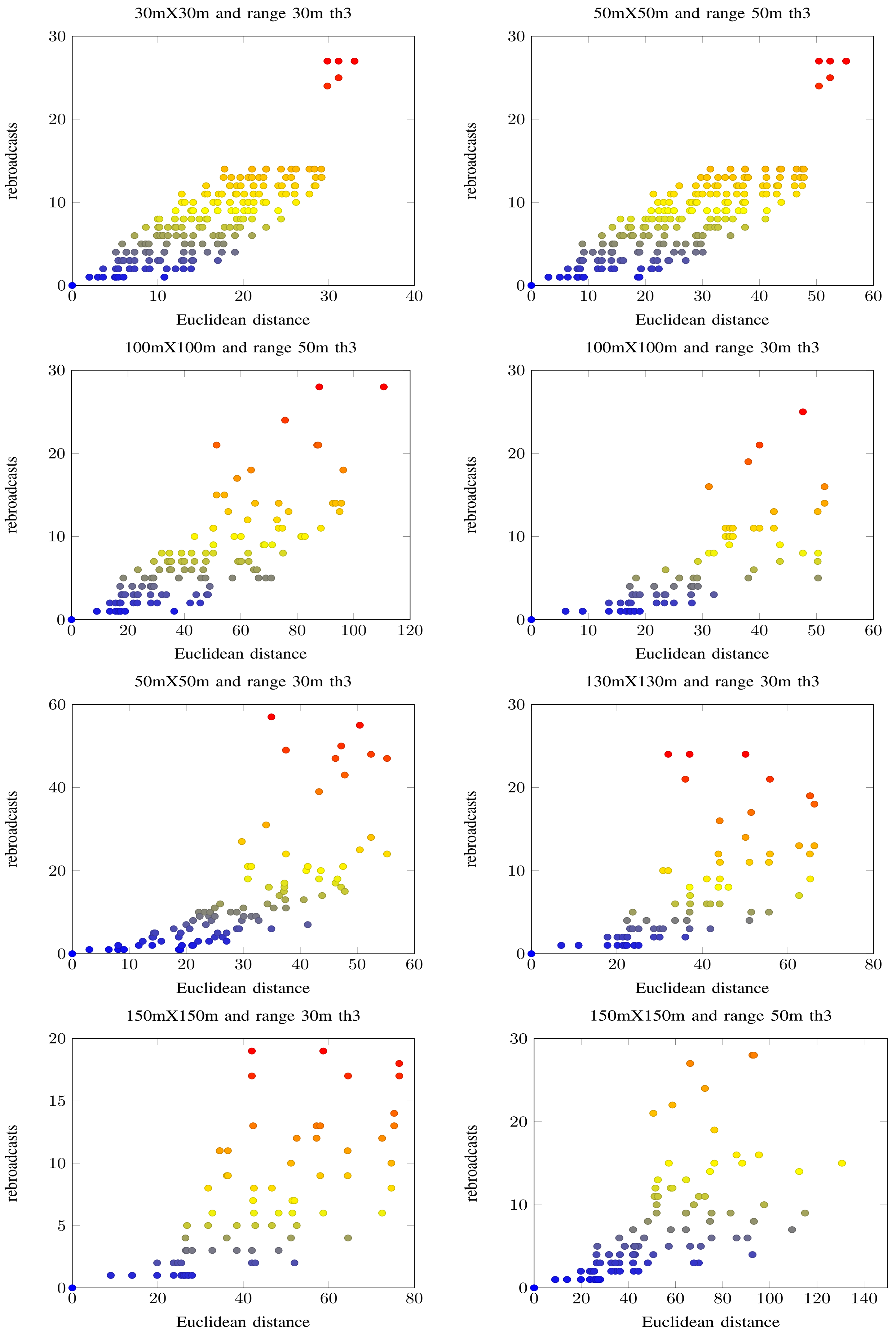

Fig. 4. Number of rebroadcasts Vs distance between node pairs

TABLE II
SIMULATION PARAMETERS

Parameter	Value
number of nodes	15
playground sizes	30m×30m, 50m×50m, 100m×100m and 150m×150m
transmission ranges	30m and 50m
threshold values	1,2,3 and 4

at least once. For unicast the terminal condition is reached when the packet reaches its intended destination. The negative feedback initiated by destination therefore is supposed to reduce the redundant rebroadcasts upon reaching the terminal condition at unicast in a MANET. Nodes other than the source and the destination that receive a chaloneInit would respond with a Chalone message. Chalone message carries the neighbor state defined in section V.

In this paper we investigate the case of unicast by specifying a source node and a destination for a data packet, thus the success of a transmission is indicated when the packet reaches the destination. We compare blind-rebroadcasting, sequence number controlled flooding and cellular automata based rebroadcasting in Section VII.

We test whether the reachability depends on node densities and chalone threshold. We first set the chalone threshold at 3 and assess reachability for different node densities by placing 15 nodes randomly on maps of different sizes and changing the transmission ranges as given in table II. Values for transmission ranges were selected based on commonly operational distances of commercial WiFi products. The node placement was decided based on common application scenarios for dense and extremely-dense MANETs.

VII. RESULTS AND DISCUSSION

Performance metric for the protocol evaluation is the number of times a particular data packet is received by all the nodes in the MANET until the specified destination is reached. The scenario at startup is for the MANET to have a single data packet originated by the specified source node. Figure 3 illustrates the obtained results for the comparison of the proposed protocol (CA protocol) against simple flooding (SNCF) and blind rebroadcasting for different node densities of the MANET. The reachability is assessed in terms of the ratio between the number of node pairs reached using the protocol and the theoretically reachable number of node pairs.

According to figure 3 the CA protocol outperforms both blind rebroadcasting and SNCF for all node densities. For example in a MANET with 50 nodes, blind rebroadcast caused the network to reach the same packet 206 times while SNCF recorded 104 times. CA protocol however reported only 23 times. Thus the CA protocols saves nearly 90% of redundant rebroadcasts compared to blind rebroadcasting whereas the saving is nearly 80% compared to SNCF. Also for node density of 100, the counts were: more than 80000 packets for blind rebroadcasting, 451 for SNCF and just 49 packets for CA protocol. Blind rebroadcasts are unacceptable for MANETs beyond 100 nodes in terms of redundant rebroadcasts as the growth of the curve is steeply exponential. Though SNCF is better compared to blind rebroadcasting, it does not perform acceptably beyond 600 node density. CA on the other hand shows a slow growing curve thus making it a better protocol for all node densities shown. Further analysis into the CA protocol alone for higher node densities such as 2000 nodes proves the satisfactory performance and the usability of our protocol in dense MANETs as the number of redundant rebroadcasts has linear and slow growth against node density.

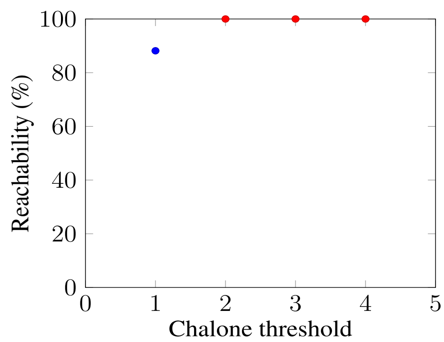

Fig. 5. Reachability as a percentage of node pairs reached with respect to theoretically reachable number of node pairs for the case of 150mX150m and range 30m

According to figure 4 it was observed that in a map of 30m×30m with range of 30m and 50m×50m with range of 50m the data points show similar clustering. Hence we define the case of map sizes of $r \times r$ with range of r where r is the transmission range as *extremely dense MANETs* that have highly specific behavioral characteristics. Therefore, these extremely dense MANETs cannot be studied alongside the dense MANETs which are the focus of this research. Rest of the graphs in figure 4 show no such special clustering of data points and are considered dense MANETs in this study.

In order to assess the impact of chalone threshold on reachability we selected the case of 150m×150m with range of 30m and evaluated for chalone threshold 1, 2, 3 and 4 as shown in figure 5. Theoretically reachable number of node pairs for this MANET configuration was 76. It was observed that chalone threshold 1 fails to deliver the data to destination for 9 of the reachable node pairs. In contrast, chalone thresholds 2 and above gives full reachability.

It was also noted in figure 6 that chalone threshold 2 and above gives the same numbers of redundant rebroadcasts. This is due to the fact that maximum number of neighbors in this configuration is 3 and that gives same number of redundant rebroadcast as of chalone threshold 2. Therefore the chalone threshold value depends on number of neighbors and should be tuned for each node for optimal reachability and reduction in redundant rebroadcasts.

VIII. CONCLUSION

Network wide packet broadcasting is an essential aspect of any routing protocol including AODV which is the Wireless Mesh Routing protocol in the latest IEEE 802.11s standard. However AODV uses flooding as the mechanism to broadcast its control packets throughout the network. We

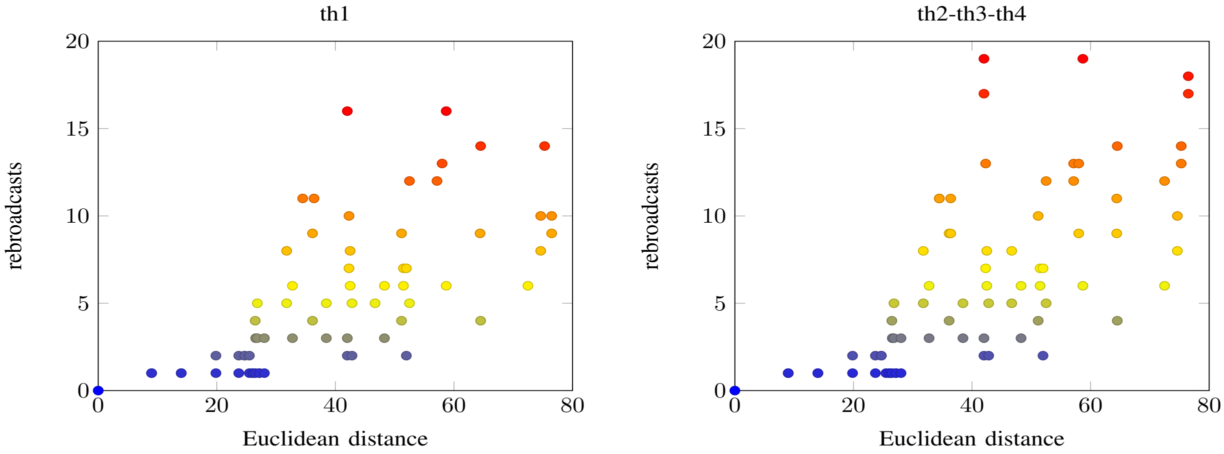

Fig. 6. Number of rebroadcasts Vs distance between node pairs for the case of 150mX150m and range 30m

found through the simulations that flooding as well as the blind-rebroadcasting is unusable at higher node densities in MANETs. In contrast we propose a Cellular Automata based broadcast mechanism inspired by biological cell proliferation in human organs. We borrow the chalone mechanism from organ growth process into MANET rebroadcasting and propose a limited broadcast scenario which gives a saving of over 80% of redundant rebroadcasts compared to both sequence number controlled flooding and blind rebroadcasting. Our protocol is also proved to be usable in MANETs with much higher node densities compared to networks that the flooding can support. The chalone threshold should be a function that partly depends on number of neighbors of each node for optimal results in terms of redundant rebroadcasts and reachability.

IX. Future Work

In the next phase of this research project, the *bio-inspired CA based MANET routing approach* presented in this paper will be tested with different mobility models applicable in practical dense MANETs. It is proposed to simulate the developed solution in a scenario such as a smart classroom of hundreds of students which allows collaborative learning.

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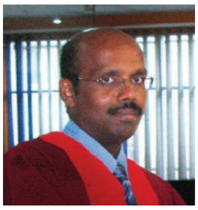
Sulochana Sooriyaarachchi was born in Anuradhapura, Sri Lanka on the 18th of October 1981. She obtained her BSc Eng. (Hons) in Electrical and Electronics Engineering from the University of Peradeniya, Sri Lanka in 2006. She then joined the Department of Computer Science and Engineering in the University of Moratuwa as a lecturer and obtained her MSc in Computer Science from the same department in 2010. She is currently pursuing her PhD in the University of Moratuwa conducting research in the area of routing and control mechanisms in mobile ad-hoc networks.



Anil Fernando leads the Video Communications group at the University of Surrey, UK. He has been working in video coding and communications since 1998 and has published more than 270 international refereed journal and proceeding papers in this area including a book on video communications. Furthermore, he has published more than 150 international refereed journal and conference papers in multimedia communications. He has contributed to several international (ROMEO, MUSCADE, DIOMEDES, VISNET, etc) projects and currently he is leading an interactive video communications project (ACTION-TV) funded by the European Union on Media communications.

Chandana Gamage is a senior lecturer in the Department of Computer Science and Engineering, University of Moratuwa, Sri Lanka. He received his PhD from Monash University, Australia, MEng from AIT, Thailand and BSc Eng Hons from University of Moratuwa and worked as a postdoctoral research scientist in Vrije Universiteit Amsterdam, The Netherlands. Dr Gamage has research interests in computer security and cryptography, enterprise software architectures and embedded systems and has published in leading conferences in these areas.