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

Sulochana J. Sooriyaarachchi*,Chandana D. Gamage†

Department of Computer Science and
Engineering
University of Moratuwa
Sri Lanka 10400
sulochanas@cse.mrt.ac.lk*,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 Smartphone devices and collaborative applications proliferate among users, the proposed dense MANET protocol could provide real benefits to Internet enabled users and devices.**

Keywords—*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 WiFi or 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].

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 brief 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 seek 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
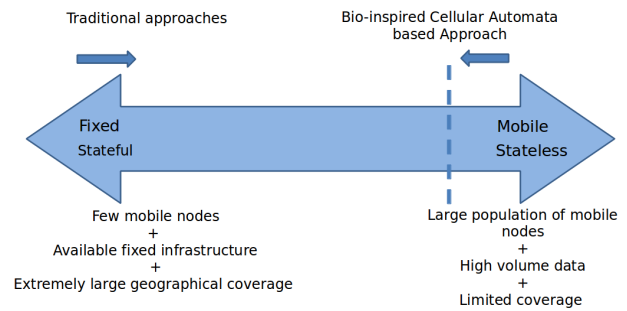

Fig. 1. Summary of comparison of our routing approach with reference to fixed-stateful and mobile-stateless routing paradigms

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 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 in [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 in [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 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

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 broadcasted the Data Packet.
Organ maturity	The state that the Data Packet reached its destination.

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 introduce the concept of packet concentration, which we define as the number of neighbors who have already broadcasted 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 obtain information in order to decide whether to rebroadcast the packet. The information requested is whether the neighbors have already rebroadcasted 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 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 rebroadcasted a specified data packet.

VI. SIMULATION

We used OMNET++ 4.4 with inet-2.2.0 for our simulation. OMNET++ is an event-driven and modular simulation framework. Topology of the desired network was created as an NED file and this process was facilitated by OMNET++ both graphically and in program code. In doing that a hierarchy of modules were used. Modules were connected via gates to create compound modules and the compound modules in turn were connected to form another level of modules in the hierarchy. Deep in the hierarchy were the Simple Modules. A Simple Module consists of a NED file, C++ source files and MSG files. NED file gives the topology and configurable parameters while the C++ source files give the functionality. MSG files provide the message formats. At compile time MSG files result in C++ classes with methods to handle messages. A simulation model was created using modules connected via gates in an NED file and a configuration file called omnetpp.ini was also created that assign values to the configurable parameters [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 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 at least once. For unicast the terminal condition is reached when the packet reaches its intended destination. The negative feedback
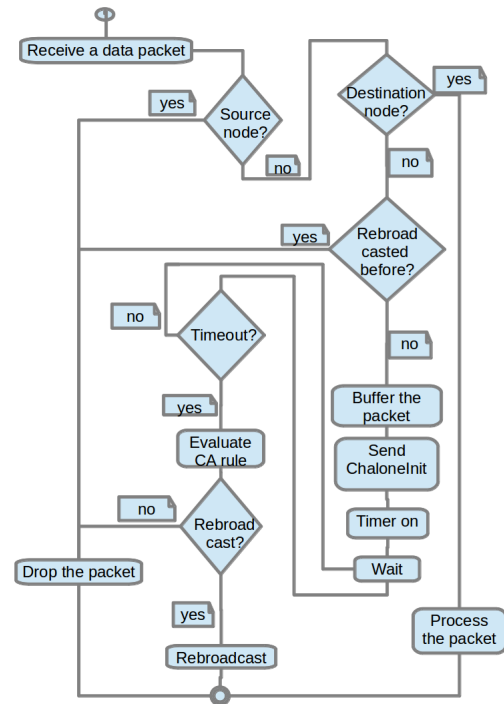

Fig. 2. Event flow at a receipt of a data packet by a node

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

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.

VII. RESULTS AND DISCUSSION

Performance metric for the comparison is the number of times a particular data packet is received by any node in the MANET till the destination is reached. The initial condition for the MANET is to have a single data packet originated by the specified source node. Figure 3 illustrates the obtained results for the comparison for different node densities of the MANET.

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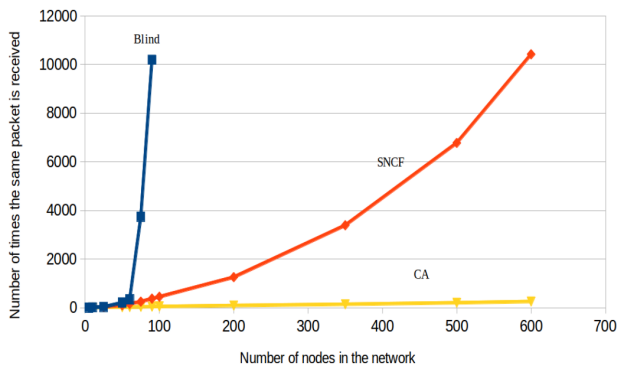
Fig. 3. Performance of Cellular Automata based Rebroadcasting (CA) protocol compared with Blind Rebroadcasting (Blind) and Sequence Number Controlled Flooding (SNCF)

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 doesn't 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.

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 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.

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.

Acknowledgments

References

[1] H. F. Wedde, M. Farooq, T. Pannenbaecker, B. Vogel, C. Mueller, J. Meth, and R. Jeruschkat, "BeeAdHoc: An energy efficient routing algorithm for mobile ad hoc networks inspired by bee behavior," in *Proc. Genetic and Evolutionary Computation Conference*, Washington, DC, USA, Jun. 2005, pp. 153–160.

[2] M. Gunes, U. Sorges, and I. Bouazizi, "ARA the ant-colony based routing algorithm for manets," in *Proc. International Workshop on Ad Hoc Networking (IWAHN 2002)*, Vancouver, British Columbia, Canada, Aug. 2002.

[3] R. Schoonderwoerd, J. L. Bruten, O. E. Holland, and L. J. M. Rothkrantz, "Ant-based load balancing in telecommunications networks," *Adapt. Behav.*, vol. 5, no. 2, pp. 169–195, 1996.

[4] G. D. Caro, F. Ducatelle, and L. M. Gambardella, "AntHocNet: an adaptive nature-inspired algorithm for routing in mobile ad hoc networks," *European Transactions on Telecommunications*, vol. 16, no. 5, pp. 443–455, Sep. 2005.

[5] Jean-yves and L. Boudec, "An artificial immune system for misbehavior detection in mobile ad-hoc networks with virtual thymus, clustering, danger signal and memory detectors," in *International Journal of Unconventional Computing*, 2004, p. 2005.

[6] P. Kefalas, G. Eleftherakis, M. Holcombe, and I. Stamatopoulou, *Formal Modelling of the Dynamic Behaviour of Biology-Inspired, Agent-Based Systems*. Idea Group Inc., 2005, pp. 243–244.

[7] N. Abramson, "Development of the ALOHANET," *IEEE Transactions On Information Theory*, vol. IT-31, no. 2, pp. 119–123, Mar. 1985.

[8] V. A. Dubendorf, *Wireless Data Technologies*. John Wiley and Sons Ltd, 2003, ch. 1.

[9] G. R. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, and B. Walke, "Ieee 802.11s: The wlan mesh standard," *IEEE Wireless Communications*, vol. 17, no. 1, pp. 104–111, Feb. 2010.

[10] Z. Liu, M. Z. Kwiatkowska, and C. Constantinou, "A biologically inspired QoS routing algorithm for mobile ad hoc networks," *International Journal Of Wireless And Mobile Computing (IJWMC)*, vol. 4, no. 2, pp. 64–75, May 2010.

[11] F. J. Mullany, L. T. Ho, L. G. Samuel, and H. Claussen, *Self-deployment, Self-configuration: Critical Future Paradigms for Wireless Access Networks*. International Federation for Information Processing, 2004, pp. 58–68.

[12] R. Subrata and A. Y. Zomaya, "Evolving cellular automata for location management in mobile computing networks," *IEEE Transactions On Parallel And Distributed Systems*, vol. 14, no. 1, pp. 13–26, Jan. 2003.

[13] C. Perkins, E. Belding-Royer, and S. Das. (2003, Jul.) Ad hoc on-demand distance vector (aodv) routing. Request for Comments: 3561. [Online]. Available: http://www.ietf.org/rfc/rfc3561.txt

[14] W. S. Conner, J. Kruys, and K. J. K. J. C. Zuniga, "Ieee 802.11s tutorial: Overview of the amendment for wireless local area mesh networking," IEEE, IEEE 802 Plenary, Nov. 2006.

[15] J. C. Lui and J.Baron, "Mechanisms limiting body growth in mammals," *Endocrine Reviews*, vol. 32, no. 3, pp. 422–440, Jun. 2011.

[16] G. Finkielstain, P. Forcinito, J. Lui, K. Barnes, R. Marino, S. Makaroun, V. Nguyen, J. Lazarus, O. Nilsson, and J. Baron, "An extensive genetic program occurring during postnatal growth in multiple tissues," *Endocrinology*, vol. 150, no. 4, pp. 1791–1800, Apr. 2009.

[17] P. J. Bryant and P. Simpson, "Intrinsic and extrinsic control of growth in developing organs," *The Quarterly Review of Biology*, vol. 59, no. 4, pp. 387–415, Dec. 1984.

[18] P. Forcinito, A. Andrade, G. Finkielstain, J. Baron, O. Nilsson, and J. Lui, "Growth-inhibiting conditions slow growth plate senescence," *Endocrinol*, vol. 208, no. 1, pp. 59–67, Jan. 2011.

[19] W. S. Bullough, "Mitotic and functional homeostasis:a speculative review," *Cancer Research*, vol. 25, no. 10, pp. 1683–1727, Nov. 1965.

[20] H. Onda, "A new hypothesis on mitotic control mechanism in eukaryotic cells: Cell-specific mitosis-inhibiting protein excretion hypothesis," *Theoretical Biology*, vol. 77, no. 3, pp. 367–377, Apr. 1979.

[21] S. Lee, "Regulation of muscle mass by myostatin," *Annual Review of Cell and Developmental Biology*, vol. 20, pp. 61–86, 2004.

[22] K. Elgjo and K. Reichelt, "Chalones: from aqueous extracts to oligopeptides," *Cell Cycle*, vol. 3, no. 9, pp. 1208–1211, Sep. 2004.

[23] D. Bakthavatsalam, D. Brock, N.N.Nikravan, K. Houston, R. Hatton, and R. Gomer, "Chalones: from aqueous extracts to oligopeptides," *Cell Science*, vol. 121, pp. 2473–2480, Aug. 2008.

[24] A. Kansal, S. Torquato, G. Harsh, E. Chiocca, and T. Deisboeck, "Simulated brain tumor growth dynamics using a three-dimensional cellular automaton," *Journal of Theoretical Biology*, vol. 203, no. 4, pp. 367–382, Apr. 2000.

[25] Y. Lee, S. Kouvroukoglou, L. V. McIntire, and K. Zygourakis, "A cellular automaton model for the proliferation of migrating contact-inhibited cells," *Biophysical Journal*, vol. 69, pp. 1284–1298, Oct. 1995.

[26] T. Alarcna, H. Byrneb, and P. Mainia, "A cellular automaton model for tumour growth in inhomogeneous environment," *Journal of Theoretical Biology*, vol. 225, no. 2, pp. 257–274, Nov. 2003.

[27] O. Mireira and A. Deutsch, "Cellular automaton models of tumor development: A critical review," *Advs. Complex Syst*, vol. 5, no. 2/3, pp. 247–268, 2002.

[28] S. Wolfram, "Statistical mechanics of cellular automata," *Reviews of Modern Physics*, vol. 55, no. 3, pp. 601–644, Jul. 1983.

[29] J. Kari, "Theory of cellular automata: A survey," *Theoretical Computer Science*, vol. 334, pp. 3–33, Nov. 2005.

[30] J. I. Barredo, M. Kasanko, N. McCormick, and C. Lavalle, "Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata," *Landscape and Urban Planning*, vol. 64, pp. 145–160, 2003.

[31] Q.-X. Liu, Z. Jin, and M.-X. Liu, "Spatial organization and evolutional period of the epidemic model using cellular automata," *Physical Review E*, vol. 74, Nov. 2006.

[32] X.-B. Li, R. Jiang, and Q.-S. Wu, "Cellular automaton model simulating traffic flow at an uncontrolled t-shaped intersection," *International Journal of Modern Physics B*, vol. 18, no. 17-19, pp. 2703–2707, 2004.

[33] R. M. Almeida and E. E. N. Macau, "Stochastic cellular automata model for wildland fire spread dynamics," in *9th Brazilian Conference on Dynamics, Control and their Applications (DINCON'10)*, Serra Negra, SP, Jun. 2010, pp. 249–253.

[34] O. Martin, A. M. Odlyzko, and S. Wolfram, "Algebraic properties of cellular automata," *Communications in Mathematical Physics*, vol. 93, pp. 219–258, 1984.

[35] N. H. Packard and S. Wolfram, "Two-dimensional cellular automata," *Journal of Statistical Physics*, vol. 38, no. 5/6, pp. 901–946, 1985.

[36] *User Manual: OMNeT++ version 4.4.1*, OMNET++, 2014.