A Linear Model for Energy-Aware Scheduling Problem Considering Interference in Real-time Wireless Sensor Networks

Maryam Hamidanvar*
Department of Computer Engineering, Arak University, Arak, Iran
maryam.hamidanvar@yahoo.com
Reza Rafeh
Department of Computer Engineering, Arak University, Arak, Iran
r-rafeh@araku.ac.ir

Received: 27/Mar/2015 Revised: 01/Nov/2015 Accepted: 23/Nov/2015

Abstract

An important factor in increasing quality of service in real-time wireless networks is minimizing energy consumption, which contradicts with increasing message delivery rate because of associating a time deadline to each message. In these networks, every message has a time deadline constraint and when the message is not delivered to its destination before its deadline, it will drop. Therefore, scheduling methods that simultaneously consider both energy consumption and time deadline constraint are needed. An effective method for reducing energy consumption is multi-hop transmission of packets. However, this method takes longer time for transmission as compared to single-hop transmission. Parallel transmission is another approach which on one hand reduces the transmission time and on the other hand increases the network throughput. However, a main issue with parallel transmission is the presence of interference among nearby nodes. In this paper, we propose a linear model (ILP formulation) for energy aware scheduling problem in real-time wireless sensor networks using parallel transmission. The main objective of the model is to reduce energy consumption and packet loss using multi-hop routing and parallel transmission. Simulation results show that the proposed model finds the optimum solution for the problem and outperforms the sequential scheduling based on the TDMA protocol.

Keywords: Energy Consumption; Parallel Transmission; Scheduling; Optimization; Routing; Interference.

1. Introduction

Wireless networks consist of nodes that communicate with each other by radio waves. Each node in the network has a limited amount of energy stored in a battery that is not rechargeable. Thus the end of the battery life denotes the end of the node's lifetime [1]. In real-time wireless networks, in addition to limitation of energy resources, the duration of the packet delivery has also a time-deadline constraint.

According to the quality of service metrics in real-time wireless networks, messages must be delivered within the specified time, otherwise they will become useless. Thus, real-time networks need to send the messages timely in the network. However, factors such as limited power supply, interference, network congestion and loss of links reduces the ability of the network to achieve the desired objectives [2].

A useful strategy to reduce energy consumption and thereby increasing the lifetime of the network is to use multiple smaller hops instead of a single long hop between source and destination. Because energy used to send a message is directly proportional to the square of the hop length [1,3,4]. Therefore, if the number of hops is increased and distance between the hops is decreased, the energy consumption will also decrease. However, using intermediate hops will increase message transmission time. So the number of intermediate hops should be set in such away as to minimize energy consumption while satisfying the time deadline constraint.

Parallel transmission of packets increases the number of packets transmitted per unit time and hence increases the efficiency of the real-time wireless network. In sequential scheduling based on TDMA protocol packets are transmitted by the source nodes sequentially [5]. Considering the possibility of parallel transmission, several source nodes can send the message simultaneously thereby increasing the efficiency of the network. Parallel transmission prevents the violation of time constraint as far as possible and in addition to that reduces the amount of energy required to transmit the message. Due to the increase in number of messages sent per unit time, more time units will be available and the message will be sent via route having more hops with less distance in between them. But parallel transmission is restricted by the phenomenon of interference in wireless networks. Because by increasing parallel transmission, probability of interference also increases. The phenomenon of interference is due to the collision of signals sent from nodes and causes loss of packets [6]. Several interference models have been proposed to model the interference in wireless networks and the presence or

* Corresponding Author

absence of interference between two links depends on the interference model used [7]. In [8] *Protocol Model* has been introduced for modeling the interference between communication links which is widely used in research. We have used this model in this paper and it will be explained in section 2.

There are two other types of interferences named *Primary Interference* and *Secondary Interference* that also cause packet loss. Primary interference occurs when a node transmits and receives messages simultaneously. Secondary interference occurs when a node receives more than one message at the same time [7].

The contrast between these limitations has put the problem of Energy-aware scheduling in the category of NP-Hard problems [3,9]. Hence, it is necessary that the conflicting objectives in the problem be addressed simultaneously as an optimization problem. Optimization problems are a group of combinational and optimization problems in which the aim is to find the best solution that satisfies all the constraints and maximize or minimize an objective function.

Recent approaches to solve the combinational and optimization problems consist of two steps: The first step is the modeling of the problem and the second step is solving the model [10]. There are three basic techniques for solving these problems: Mathematical Methods (MM), Constraint Programming (CP) and Local Search (LS). Each of these techniques has its own advantages and disadvantages. Among these methods, mathematical methods have particular importance due to their high efficiency. However, a linear model is required for the problem but formulation of the combinational and optimization problems as linear model is difficult [11].

The works related to scheduling and routing of wireless networks can be grouped according to their objective function. In some studies the objective is to increase efficiency and reduce end to end delay regardless of the energy consumption and in others it is to reduce energy consumption. In [9] an Integer Linear Program (ILP) formulation has been presented for the problem of energy-aware scheduling in real- time wireless networks, without taking into consideration the interference phenomenon. In this method the nodes transmit messages in a sequential manner and there is no possibility of parallel transmission. In [1] to create a balance between energy consumption and time delay a non-linear model based on Concentric Circular Bands (CCBs) has been proposed. In this study, the effect of the interference and parallel transmission has not been taken into consideration. In [12], a nonlinear model has been proposed which aims at reducing overall energy consumption in clustered WSNs and then based on results obtained by solving the model an algorithm has been suggested to obtain minimum latency. In [5] a scheduling method for parallel transmission to multiple destinations is provided that improves the network performance as compared to the sequential TDMA method. In [13], to maximize throughput, authors have considered joint routing, channel assignment and collision free scheduling of links. In [7], solutions based on the idea of graph coloring for the problem of scheduling and routing of wireless networks have been proposed in order to increase efficiency but without considering the energy consumption. In [14] authors have considered a routing tree and proposed two delay efficient algorithms to create interference-free scheduling for data aggregation.

Most models and methods that have been proposed for the problem of scheduling real-time wireless networks have considered either reduction in energy consumption or increase in the number of delivered packets separately. Moreover, most of the existing methods are not suitable because of not considering time constraint specific to each message in real-time networks. Because in these methods usually the reduction in end to end delay or increase in number of packets transmitted is considered for all messages in a specific time interval. While in real-time wireless networks, each message has its own time constraint that may be different or identical to that of the other messages. As a result, the priority of data transmission may vary according to the various time deadlines. Another problem that can be seen in most of the previous research is ignoring the remaining energy of nodes in routing. This results in nodes lacking sufficient energy to be used in the selected route.

In this paper, linear modeling (ILP formulation) of the problem by considering both the energy consumption and time constraints has been performed. The proposed model aims to minimize energy consumption and reduce the number of lost packets by utilizing the strategy of parallel transmission and multi-hop routing.

The model is solved using Simplex method. Implementation results show the improved efficiency of scheduling by the proposed model as compared with sequential scheduling approach based on TDMA protocol. The model is able to determine the optimal route for each message and parallel scheduling keeping in view the limitations of the network.

Rest of the paper is organized in this way: In Section 2, we review some important concepts in real-time wireless networks. Section 3 describes the problem and its constraints. The section 4 of the paper describes the assumed network model. Section 5 describes the new proposed model. In section 6 we will evaluate the proposed model and discus the results obtained by solving the model. Finally Section 7 concludes the paper.

2. Energy-Aware Scheduling Problem

The problem of energy-aware scheduling with parallel transmission capability can be described as following.

1. Determine the optimal route for each message using multiple hops to reduce energy consumption while keeping in view the time constraint of each message.
2. Allocating units of time according to time constraint of messages and capability of parallel

transmission to increase the network throughput. While allocating units of time, priority should be given to messages according to their time deadlines.

Constraints of the problem are [7,15]:

1. The receiver node should be in the communication range (radio range) of the transmitter node.
2. A node cannot receive more than one message at the same time.
3. A node cannot transmit more than one message at the same time.
4. A node cannot transmit and receive messages simultaneously.
5. The nodes located in the interference range of each other should not be active at the same time.
6. Scheduling and routing of a message should be done before the time deadline of that message because every message is valid only until its time deadline. Thus continuing scheduling and routing after the time deadline of the message is useless.
7. Only nodes having enough energy are able to transmit and receive the messages.

Objectives of the problem are:

1. Minimizing the energy consumption of the network to transmit messages.
2. Maximizing the number of successfully delivered messages in specified time.

Satisfaction of the objective function reflects the quality of scheduling. This means that among the existing solutions, a solution that has the lowest energy consumption as well as the lowest number of packet loss offers optimal scheduling.

3. The Network Model

In the assumed network nodes are static and distributed randomly in a two-dimensional plane and geographic coordinates of each node is known. Each node has its own specific initial energy and transmission range that may be the same or different from those of the other nodes. Energy used by every node in each transmission is calculated by the following equation [9]:

$$E_{tr} = Cd^2 \qquad (1)$$

Where d is the distance between transmitter and receiver node and C is a constant coefficient that depends on the message length and physical condition of the network. In addition to the energy consumed for transmission, trace amount of energy is used by the receiving node while receiving the message and by idle nodes. But this amount is negligible as compared to energy used for transmission, so we have ignored it in this research.

In the assumed model all the nodes use shared wireless medium that is divided into equal time slots. Transmitter nodes that do not interfere with each other can access the shared wireless medium simultaneously. In the networks where the nodes use a single channel, each node can transmit message to all the neighboring nodes in a time slot [15].

Simultaneous activity of nodes that are located in the interference range of each other result in interference. According to the interference model, transmission and interference range of nodes may be equal or different from each other. In this paper, protocol model is used for modeling the interference between communication links. In this model transmission power of the node varies dynamically according to its distance from the receiver node. As a result interference range also varies according to the transmitter-receiver distance. According to this model if a node v_i transmits to a node v_j, transmission will be successfully received by node v_j if:

$$\left|v_k - v_j\right| \geq (1+\Delta)\left|v_i - v_j\right| \qquad (2)$$

Where $\left|v_i - v_j\right|$ is the Euclidean distance between node v_i and node v_j. The constant parameter $\Delta > 0$ denotes guarded zone specified by the protocol to prevent collision from neighboring node. v_k denotes every node simultaneously transmitting at the same time in the same channel [8].

In the protocol model, transmission from node i to node j is successful only if no other node within the interference range of node j is transmitting at the same time [16].

All communication links in the network are assumed reliable and without noise.

All of the transmitted messages in the network have the same length with the message size of L bits. Time deadline and the source-destination of each message may be the same or different from other messages. Transmission of a message in each hop takes a unit time and is not dependent on the distance between sending and receiving node. It is assumed that the duration of each time slot is equal to the maximum time needed for transmission of a message between the two farthest nodes in the environment. Therefore, each message will be allocated a full time slot even if the time taken by the transmission of the message is less than the allocated time slot.

4. ILP Formulation

In this section the problem is formulated as integer linear program (ILP) keeping in view the characteristics and limitations of the network.

In energy-aware scheduling problems the total energy consumption and the number of packets delivered are calculated in a time window. In this model, size of the time window is equal to the longest time-deadline of existing messages in the network.

Parameters

Msg: Set of messages

Each message is shown by a tuple as:

(m, src, des, dln) where

m: id of message.

src: Source of message.

des: Destination of message.

dln: Time deadline of message.

Time: Size of the time window.
Nodes: Set of the nodes existing in the network.
R_i: Transmission range of node *i*.
E_i: The initial energy of node *i*.
$d_{i,j}$: Euclidean distance between nodes *i* and *j*.

Variables

Solution of the problem is presented as a four dimensional binary matrix.

$$X_{Time, Nodes, Nodes, Msg}$$

$$X_{t,s,d,m} = \begin{cases} 1 & \text{If node s transmits message m to node d} \\ & \text{during timeslot t} \\ 0 & \text{Otherwise} \end{cases}$$

The first dimension is time, second dimension is transmitter nodes, third dimension is receiver nodes and the fourth dimension is messages.

Constraints for ILP formulation are as follows:

- Equation (3) imposes limitation of transmission range for each node and ensures that receiver node is located within the transmission range of the sender node.

$$\forall i \in Nodes, \forall t \in Time, \forall k \in Msg, \forall j \in Nodes$$
$$X_{t,i,j,k} * d_{i,j} \le R_i \quad (3)$$

- Equation (4) ensures that a node cannot transmit and receive simultaneously. It also restricts sending and receiving more than one message by the node at a time.

$$\forall t \in Time, \forall i \in Nodes$$
$$\sum_{j \in Nodes} \sum_{k \in Msg} X_{t,i,j,k} + \sum_{s \in Nodes} \sum_{k \in Msg} X_{t,s,i,k} \le 1 \quad (4)$$

- According to the protocol model, equation (5) imposes that if simultaneous transmission of two sender nodes (such as node *i* and node *s*) is interfering only one of them is allowed to transmit. As stated in equation(2) about protocol model, interference occurs when the distance between the sender node *i* and the receiver node *j* multiplied by a constant 1+Δ is greater than the distance between the receiver node *j* and another transmitting node say node *s*. For example if node *i* is the sender node and node *j* is the corresponding receiver node, and another node s is also transmitting simultaneously and the distance between the node *s* and the node *j* is less than the product of distance between the node *i* and node *j* multiplied by a constant(1+Δ), interference will occur. Equation (5) prevents such interferences.

$$\forall t \in Time, \forall i \in Nodes, \forall s \in Nodes, \forall j \in Nodes$$
$$where\ i \ne s \ne j\ and\ d_{s,j} < (1+\Delta) * d_{i,j}$$
$$\sum_{k \in Msg} X_{t,i,j,k} + \sum_{m \in Msg} \sum_{d \in Nodes} X_{t,s,d,m} \le 1 \quad (5)$$

- Constraint (6) ensures that scheduling and routing of the messages is done before its time deadline. It means that the total unit times elapsed for each message must be less than its allocated time deadline.

$$\forall k \in Msg, \forall t \in Time_{where\ t > dln_k}$$
$$\sum_{i \in Nodes} \sum_{j \in Nodes} X_{t,i,j,k} = 0 \quad (6)$$

- Equation (7) determines energy source limitation for each node to transmit.

$$\forall i \in Nodes$$
$$\sum_{t \in Time} \sum_{k \in Msg} \sum_{j \in Nodes} X_{t,i,j,k} * C * (d_{i,j})^2 \le E_i \quad (7)$$

- Constraint (8) ensures that each node either sends a message once only or not at all. This means that if node *s* sends a message *k* to node *d* in time *ti*, then the node *s* will not send the message *k* again to node *d* or any other node in time *tj*.

$$\forall i \in Nodes, \forall k \in Msg \sum_{t \in Time} \sum_{j \in Nodes} X_{t,i,j,k} \le 1 \quad (8)$$

- Equation (9) imposes that for each intermediate node the total number of incoming messages minus the total number of outgoing messages before their time deadline is zero i.e. the number of input messages and the number of output messages is equal. In this way equation (9) ensures that a continuous path is selected for each message. This means that each message that enters an intermediate node before deadline must be forwarded by the same intermediate node.

$$\forall k \in Msg, \forall i \in Nodes_{where\ src_k \ne i \ne des_k}$$
$$\sum_{s \in Nodes} \sum_{\substack{t_1 \in Time \\ where\ t_1 < dln_k}} X_{t_1,s,i,k} - \sum_{d \in Nodes} \sum_{\substack{t_2 \in Time \\ whete\ t_2 \le dln_k}} X_{t_2,i,d,k} = 0 \quad (9)$$

- Constraint (10) ensures that the sending time of a message by the intermediate node is after the receiving time of that message.

$$\forall k \in Msg, \forall i \in Nodes_{where\ src_k \ne i \ne des_k}$$
$$\sum_{\substack{t_2 \in Time \\ where\ t_2 \le dln_k}} \sum_{d \in Nodes} X_{t_2,i,d,k} * t_2 - \sum_{\substack{t_1 \in Time \\ where\ t_1 < dln_k}} \sum_{s \in Nodes} X_{t_1,s,i,k} * t_1 \ge 0 \quad (10)$$

- Equations (11) and (12) impose that the message does not enter the source node and does not leave the destination node, respectively.

$$\forall k \in Msg, \forall i \in Nodes$$
$$\sum_{t \in Time} X_{t,i,src_k,k} = 0 \quad (11)$$

$$\forall k \in Msg, \forall i \in Nodes$$
$$\sum_{t \in Time} X_{t,des_k,i,k} = 0 \quad (12)$$

Objective function of the problem:

The objective function in equation (13) aims to minimize energy consumption and packet loss. The first part of the equation (before minus sign) calculates energy consumption for transmission of messages and the second part of the equation calculates number of delivered messages.

Minimize

$$\sum_{t\in Time}\sum_{i\in Nodes}\sum_{j\in Nodes}\sum_{k\in Msg} X_{t,i,j,k} * C * \left(d_{i,j}\right)^2 - M * \sum_{k\in Msg}\sum_{i\in Nodes}\sum_{\substack{t\in Time \\ \text{where } t\leq dln_k}} X_{t,i,des_k,k} \quad (13)$$

In this equation M is a big positive number that is used as weighted coefficient for the delivered messages. The reason to use such a big coefficient is that the energy consumed by the network to send messages is much greater than the number of messages delivered, so routing causes the objective function to be always positive and the minimum value for the objective function is possible when no message is routed to its destination so that no energy is used in the network. Therefore, in the absence of the weighted coefficient for the number of delivered messages no routing is done so that the objective function remains zero. Use of big coefficient results in negative objective function value and thus maximizing the number of messages delivered without time violation.

5. Results

In this section results obtained by solving the proposed model are evaluated in different scenarios. The linear model is solved by using the ILOG CPLEX 12.2 software. The presented model is evaluated in terms of energy consumption and the number of messages delivered as compared to sequential TDMA based scheduling method. Improvement of scheduling by the proposed model because of using parallel transmission is demonstrated as compared to sequential scheduling. The reason for not comparing the results obtained by solving the model with other relevant work is different scenario of the problem because of considering more constraints as explained in section 1.

In the main scenario the nodes are distributed randomly in a two-dimensional region measuring $200 \times 200m^2$ Transmission range of each node is assumed to be 100m. Values of the parameter Δ in protocol model and M in objective function are assumed to be 10^{-9} and 10000 respectively. Each of the messages in the network can have the same or different source, destination and time deadline as compared to other messages.

Equation (1) is used to compare the energy consumption and the value of the parameter C is considered equal to 0.2. The number of nodes varies between 10 and 40, and the effect of number of nodes is evaluated on the quality of scheduling. The reason to limit the number of nodes to 40 is lengthy execution time of the proposed model and memory usage complexities. The number of messages is also decreased because of the same reason. This is due to the fact that by increasing the number of nodes and messages, the number of variables of the problem increases that results in lengthy runtime and high memory usage. When the number of nodes is 10, the solver can solve the model for routing more than 200 messages in reasonable time (less than 10 minutes). But when the number of nodes is increased, the solver will find the solution of the problem with less number of messages. For 20, 30 and 40 set of nodes, the solver can solve the model with about 65, 15 and 5 messages respectively. For evaluating the effect of number of nodes, we have limited the number of messages to 5 so that the solver can solve the model with all the four sets of 10, 20, 30 and 40 nodes.

For each of the effective factors in evaluating the model, 20 different sets are generated randomly and the average values are inserted in evaluation charts as final result.

In Figure 1 the percentage of messages successfully delivered by two methods are compared with each other. As can be seen the percentage of messages delivered by linear model is greater than the percentage of messages delivered by sequential scheduling in all conditions. The reason for this difference is the parallel transmission and the increase in number of transmitted messages per unit time by the proposed model. By the solution provided by the suggested model, all the messages that are routed will definitely reach destination within time deadline. It means that the messages with no possibility of delivery in time will not be routed at all. Because the routing of such messages will only serve to waste energy and time of the network and ultimately the message will not be delivered to its destination.

In the worst case, when parallel transmission is not possible, the number of messages delivered by proposed model is equal to the number of messages delivered by sequential scheduling and never less than that.

Increase in number of nodes has resulted in the increase of the delivered messages. Because increase in the number of nodes has resulted in increase in the density of nodes in the region, hence additional nodes are available in the transmission range of the nodes. As a result the messages that could not be transmitted due to limited radio range of the nodes are now sent by multi-hop transmission.

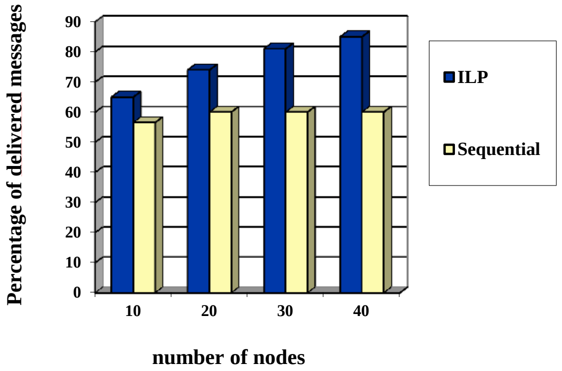

Fig. 1. Percentage of delivered messages

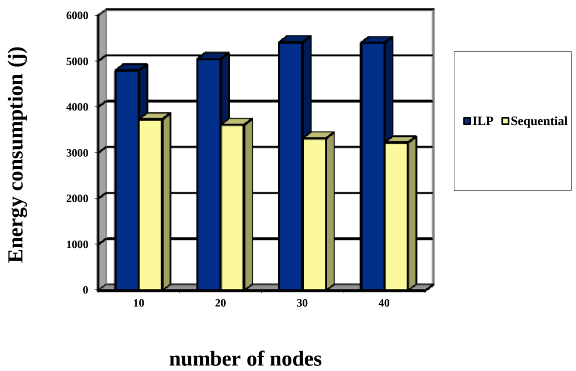

Fig. 2. Energy consumption

In Figure 2 comparison of average energy consumption by proposed model (ILP) and sequential scheduling is done.

In this figure increase in consumption of energy by the proposed model is due to the increase in percentage of delivered messages. It is obvious that more energy will be consumed to send more messages. In the sequential method due to lack of parallel transmission some packets do not meet the time deadline and are dropped. So no energy is consumed for transmission of such messages.

In certain conditions it is possible that in spite of the increase in number of transmitted messages in the proposed model, energy consumption is less than the sequential method. Due to the use of parallel transmission in the proposed model, more time slots will be available and the message will be sent via route having more hops with less distance in between them that results in decrease in energy consumption. For example there are two messages with time deadline of 2 seconds in the network. In sequential scheduling, to avoid violation of the time deadline, each message must be transmitted by a single hop. But in the proposed model, if there is no interference, each of the messages can be transmitted simultaneously using two intermediate hops and will result in reduced energy consumption.

As explained earlier, by increasing the number of nodes in the network, percentage of delivered messages also increases. Naturally, transmission of these additional messages consumes energy that increases the total energy consumption.

However, in some cases it is possible that by increasing the number of nodes, total energy consumption decreases. The reason for this reduction in energy consumption is that the messages previously routed have possibility of using more intermediate hops due to the increased number of nodes. Sometimes the reduction in energy consumption is of so considerable amount that even after compensating for the additional energy required for the transmission of additional messages, total energy consumption is less than that of the scenario when the number of nodes and messages were fewer.

6. Conclusions

In this paper, energy-aware scheduling problem is modeled as linear while keeping in consideration the phenomenon of interference. The proposed model is capable of determining the optimal route for each message by using parallel transmission and multi-hop routing. Therefore, scheduling provided by solving the proposed model can be used as a criterion for evaluating the quality of solutions provided by other methods and algorithms for the problem. But solving the model has high complexities in terms of runtime and memory resources. For this reason, in future we intend to solve this problem by using other existing method for combinational and optimization problems such as meta heuristic methods.

References

[1] H.M. Ammari, "On the energy-delay trade-off in geographic forwarding in always-on wireless sensor networks: A multi-objective optimization problem". Computer Networks, 2013. 57(9): pp. 1913-1935.

[2] A. Mahapatra, , K. Anand, and D.P. Agrawal, "QoS and energy aware routing for real-time traffic in wireless sensor networks", Computer Communications, 2006, 29(4): pp. 437-445.

[3] G.S.A. Kumar, "System Level Energy Management of Networked Real-Time Embedded Systems", Ph.D. thesis, Computer Engineering Department, Iowa State University, Ames, 2009.

[4] G.S.A.Kumar, G. Manimaran, and Z. Wang, "Energy-aware scheduling with deadline and reliability constraints in wireless networks", Broadband Communications, Fourth International Conference on IEEE, BROADNETS 2007.

[5] G.D.Nguyen, et al., "Parallel TDMA Scheduling for Multiple-Destination Wireless Networks". IEEE Transactions on Wireless Communications, 2011. 10(11): pp. 3843-3851.
[6] M. Nazarzadeh, "Proposing an Energy-Aware Scheduling Method with Parallel Transmission capability in Real-time Wireless Network ", M.S.thesis, Islamic Azad University, Malayer, 2013.
[7] Y. Wang, et al., "Interference-aware joint routing and TDMA link scheduling for static wireless networks", IEEE Transactions on Parallel and Distributed Systems, 2008, 19(12): pp. 1709-1726.
[8] P. Gupta, and P.R. Kumar, "The capacity of wireless networks", IEEE Transactions on Information Theory, 2000, 46(2): pp. 388-404.
[9] G.S.A. Kumar, G. Manimaran, and Z. Wang, "Energy-aware scheduling with probabilistic deadline constraints in wireless networks". Ad Hoc Networks, 2009. 7(7): pp. 1400-1413.
[10] M.Davoudzadeh, "Using Bee Colony Optimization Algorithm for Solving the University Timetabling Problem", M.S. thesis, Computer Engineering Department, Islamic Azad University, Arak, 2011.
[11] R. Rafeh, et al., "Towards the new modelling language Zinc", in open source developers: monash university, melbourne, 2005.
[12] L. Shi, A. O.Fapojuwo, "TDMA Scheduling with Optimized Energy Efficiency and Minimum Delay in Clustered Wireless Sensor Networks", IEEE Transactions on Mobile Computing 9, no.7, 2010, pp. 927-940.
[13] M. Al-Ayyoub, H. Gupta, "Joint Routing, Channel Assignment, and Scheduling for Throughput Maximization in General Interference Models", models. IEEE Transactions on Mobile Computing 9, no.4, 2010, pp. 553-565.
[14] X. Xi, X-Y. Li, M. Song "Efficient Aggregation Scheduling in Multihop Wireless Sensor Networks with SINR Constraints", IEEE Transactions on Mobile Computing 12, no. 12, 2013, pp. 2518-2528.
[15] C.J.L. Arachchige, et al., "Minimal time broadcasting in cognitive radio networks", Distributed Computing and Networking, 2011, pp. 364-375.
[16] S. Fan, L. Zhang and Y. Ren, "Optimization-Based Design of Wireless Link Scheduling With Physical Interference Model", IEEE Transactions On Vehicular Technology61, no. 8, 2012, pp. 3705-3717.

Maryam Hamidanvar received her B.Sc. degree in Software Engineering from Bu-Ali Sina University (BASU), Hamedan, Iran, in 2012, and her M.Sc. degree in Software Engineering from Arak University, Arak, Iran, in 2014. Her research interests include modeling of the combinational and optimization problems, modeling languages, constraint programming, wireless networks and application programming.

Reza Rafeh is a faculty member in the Department of Computer Engineering at Arak University (Iran). He got his B.Sc. and M.Sc. in Software Engineering from Sharif University of Technology (Iran). He received his Ph.D. in computer science from Monash University (Australia). His interesting areas are compiler design, constraint programming and theorem proving. He is the chief editor of Software Engineering Journal as well as an editorial board of Soft Computing Journal.