FLAME: A Flexible and Low-Power Architecture for Wireless Mesh Networks

Seyed Dawood Sajjadi Torshizi[1], Sadra Mohammadalian[2], Fazirulhisyam Hashim[1], and Subramaniam Shamala[2]

[1] Department of Computer and Communication System Engineering, Faculty of Engineering, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia
dawood.sajjadi@ieee.org, fazirul@eng.upm.edu.my
[2] Department of Communication Technology and Networks, Faculty of Computer Science and Information Technology, Universiti Putra Malaysia (UPM)
sadra.m.alian@gmail.com, shamala@fsktm.upm.edu.my

Abstract. Nowadays, Wireless Mesh Network (WMN) is known as a promising technology for fast, robust and low-cost deployment of network infrastructures. Establishment of high throughput and reliable links, deduction of the interference effect and saving the energy are some of the serious concerns in construction of WMNs. Although, dominant solutions in organizing these networks are based on omnidirectional antennas, utilizing the directional antennas due to their potential advantages in terms of attaining higher throughput and coverage is a real interest in WMNs. In this paper, a novel framework for building well-organized and low power consumption WMNs by means of flexible directional antennas is presented which to the best of our knowledge can be considered as an innovative solution in deployment of optimized and green WMNs. Acquired preliminary results substantiate not only the efficiency of offered framework in flexible implementation of mesh networks, but also in construction of high-throughput and resilient WMNs.

Keywords: WMN, directional antenna, power conservation, NS3 simulator, QoS, battery lifetime.

1 Introduction

Recently, Wireless Mesh Networks (WMN) is considered as a propitious solution for rapid and cost-effective deployment of various network services and applications. The multi-hop wireless links, which are constructed by means of the familiar 802.11a/b/g/n standards, constitute the primary elements of this paradigm. Particularly, this kind of wireless networks is similar to the wired network in the sense that it is distinguished by a static topology with infrequent changes.

Over recent years, using directional antennas in the deployment of wireless mesh networks has attracted a lot of interests. Directional antennas in comparison to the omnidirectional antennas are able to cover more larger transmission range and also use more spatial reuse to achieve higher throughput. Through this commodity, the

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wireless nodes can communicate to each other with less interference and get more radio coverage, simultaneously. Hence, by establishment of long distance links, fewer numbers of routing hops will be used which, it leads to the elevation of QoS for determined services.

In this research, we attempted to take advantage of directional antennas by proposing a dynamic sectorial coverage in the deployment of a WMN infrastructure. In fact, we propose a new architecture based on directional antennas, which provides self-healing and on demand connectivity among all utilized mesh routers to improve the overall QoS and reduce the amount of consumed power within each mesh router. Simulation as one of the most dominant methodologies was chosen to direct our experiments over the proposed solution. In our simulation, we regarded only the topology of stationary nodes, which decreases the complexity level of assessment procedure in the early experiments. Demonstrated simulations results under NS3 confirm that applying the offered framework to dynamic directional antenna and flexible transmission power improves the functionality of mesh networks in several aspects and outperforms omnidirectional antennas in terms of energy consumption and coverage areas. The main contribution of this work can be regarded as the provisioning of a green architecture for resilient deployment of wireless mesh networks with respect to attain the maximum achievable throughput between every determined points. Since one of the main global concerns of recent research topics is the practice of selecting energy-efficient networking technologies and minimizing resource usages whenever possible, we believe that the offered framework provides a proper solution for better construction of mesh networks.

The remainder of this paper proceeds as follows. In the next section, well-known related works about the utilization of directional antennas in construction of wireless mesh networks are discussed. Then in section 3 the proposed framework and its major components are described in detail. Towards evaluating the fundamental functionalities of offered solution, multiple simulation scenarios are conducted in the succeeding section. In section 5, acquired results and relevant discussions for performed experiments are deliberated. Finally, concluding statements and future plans are presented in section 6.

2 Related Works

So far, several research works have been conducted on employment of directional antennas to promote regular performance metrics in wireless mesh networks. As an instance, DMesh [1] is one of the first architectures, which has integrated the spatial separation of directional antennas with frequency segregation of non-overlapping channels to enhance the throughput of WMNs. The authors (through directing different scenarios over simulation and test-bed environments) have represented the promotion of attained throughput by means of the offered solution to more than 200% compared to the mesh networks, which are based on omnidirectional antennas. Also, S. Muthaiah et al. in [2] presented a case study on using smart (directional) antennas to improve spatial reuse and coverage range in addition to the achieving higher throughput at lower powers.

Another related research is directed in [3] through simulation, which in a multi-radio multi-channel scenario, authors utilized directional antennas in each mesh router to degrade the amount of interference and provide simultaneous transmission capability to promote physical data rate and consequently aggregate throughput in the mesh network. In the performed simulation, it was supposed that the transmission power (TX power) in each node is tuned appropriately to decrease the interference effect just to the adjacent nodes. J. Zhang directed related researches in [4] and [5] to analyze the capacity of mesh networks with Omni and directional antennas. Authors proposed a mathematical model in [4] to show the capacity enhancement of WMN by means of directional antennas.

At the other work [5], an algorithm was presented to increase the traffic delivery ratio of mesh nodes by adjusting the orientations of directional antennas in the mesh network. It is assumed that each node has multiple antennas, which by interconnecting various nodes to each other, the delivery ratio can be improved up to 280%. It should be noted that after running each round of the offered algorithm, the antenna orientation and mesh topology will be rearranged just to ameliorate the end-to-end throughput within the simulation, but the authors didn’t present any practical mechanism for adjustment procedure in the real scenarios. Furthermore, in [6], [7] and [8] the scholars through modeling and simulation represented the efficaciousness of MIMO and directional antennas in different aspects of WMN operations.

H. Okada et al. also in [9] and [10] proposed a 3-sectore antenna system for utilization in multi-radio multi-channel WMN. Through extensive analytical modeling and test-bed implementations, they proved the enhancement of several metrics especially throughput by means of sector antennas, but they didn’t investigate the efficiency of their offered solution in term of power consumption. J. Ben-Othman et al. directed analogous works in [11] and [12] by means of NS3 simulator for using sector antennas to enhance overall QoS. Customized versions of OLSR [13] and IEEE 802.11s [14] routing protocols were employed in several scenarios while utilization of directional antennas were taken into account.

In addition to the aforementioned researches, multiple works performed over channel assignment and topology control in wireless mesh networks which directional antennas were regarded as the key design component [15-18]. In [17], a 3-step topology control mechanism for adjusting the orientation of directional antennas and channel allocation is proposed. The offered solution facilitates the construction of mesh networks and maximizes the delivery ratios of traffic demands. It begins by organizing a set of routing trees to balance the traffic among the tree links. Then, the interface allocation for each node of tree with regards to the load distribution among served links by that node will be done. At last, it performs the antennas orientation and channel assignment to mitigate the interference while covering all specified destination nodes. Several relevant researches were inspired from this scheme, which tried to decrease its complexity and improves its topology formation in terms of various performance metrics such as end-to-end delay and Packet Delivery Ratio (PDR) among mesh nodes [18].

Almost in all mentioned works on using directional antennas in WMNs, the major concern of scholars was promotion of throughput and PDR among the mesh routers and energy conservation through dynamic assignment of transmission power and antenna orientation has not been fully investigated yet. Hence, in the next section, the main focus of the proposed architecture is achieving to the higher level of power conservation and system efficiency through dynamic allocation of TX power and antenna orientation in each radio. Different components of offered solution and their respective functions are deliberated in details in section 3.

3 Proposed Architecture

The key challenge in deployment of wireless mesh networks is how to construct a network that connects all nodes to the mesh gateways, such that the end-to-end throughput of the network is maximized. The antennas orientation alignment and channels assignment procedures can be regarded as the major steps of this process, which are dependent to each other. Another serious concern in implementation of mesh networks, especially those are deployed in none-urban and low population areas, is power conservation and utilizing renewable energies to feed different network elements.

Proposed mechanism in this paper is applicable for mesh networks with stationary nodes, which are using single or multiple radios to establish wireless links in different channels. The essence of the offered solution in power saving is based on using the receiver sensitivity values of utilized wireless adapters and finding the optimum required transmission power on each radio. To attain this goal, the Received Signal Strength Indication (RSSI) values of peer nodes will be monitored and compared with predefined thresholds quantities, continuously.

Table 1. Typical QoS parameters for well-known applications [19]

Type	Application	Data Rate	Latency	Jitter	Loss
Audio	Conversation	4,64 kbps	< 150 ms	< 1ms	< 3%
	Speech/Music	5,128 kbps	< 10 s	< 1ms	< 1%
Video	Real-time video	16,384 kbps	< 10 s	< 1ms	< 1%
Data	Interactive game	< 8 kbps	< 250 ms	n/a	0 %
	Web browsing	< 80 kbps	< 250 ms	n/a	0 %
	Email	< 80 kbps	< 4 s	n/a	0 %

In fact, based on the offered algorithm, there is an initial network topology, which all nodes are placed and configured to setup a basic mesh topology at the beginning of the experiment. Then, all mesh routers start tuning procedure of TX power values in their radios while they should maintain the quality of established wireless links with regard to the predetermined QoS thresholds. Considering the type and sensitivity of utilized applications over mesh networks, appropriate margins can be defined to verify the acceptable level of QoS for wireless links. TABLE I demonstrates some of the most familiar network applications and their corresponding required QoS parameters to present a reliable service to the end-users.

Offered solution is divided into interconnected steps among which construction of a multi-radio multi-channel mesh network topology is the first step. In the next step, reduction of the transmission power to conserve much more energy will be begun. This process will lead to the mitigation of the interference effect on the link quality and attaining to the maximum link throughput in each node. Fig. 1 represents the essential components of offered architecture, with the Antenna Alignment Engine (AAE) as the key section, which integrates the rest of the system's components.

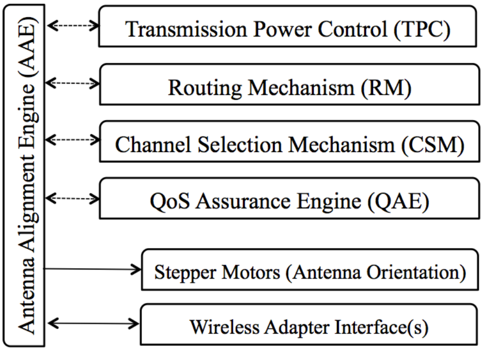

Fig. 1. Essential components of proposed architecture

Since antenna alignment procedure has a direct impact on the functionality of other system components, they can be controlled and optimized through this entity. RM and CSM respectively as the routing and channel selection modules in the aforementioned framework accommodate basic addressing and connectivity among mesh routers which regarding the number of nodes and network topology can be chosen as static or dynamic.

It should be noted that although multiple energy efficient and battery aware routing schemes have been presented for wireless mesh networks so far [20-23], almost all of them applied only over Omni directional antennas and none of them proposed a practical approach for deployment of their offered mechanisms. According to the predetermined QoS margins, QAE module is in charge of quality guarantee for established links in each mesh routers. Mentioned values in TABLE I can be considered as a reliable reference for operation of this component. By quality degradation of any wireless links, the transmission power of corresponding radio should be increased which this task will be done through TPC component after notification of QAE module. Then, the determined level of TX power based on proposed algorithm will be committed over each radio adapter by means of AAE module The last major component of the proposed framework, which distinguishes it from other similar works, is the Antenna Alignment Engine (AAE) module. For better explanation of this element, a multi-radio multi-channel mesh topology is displayed in Fig. 2. As it is shown in Fig. 2 (a), 8 nodes, which each one is equipped with 2 radios, are interconnected to each other through wireless links that operate in different 2.4 GHz frequency channels. Suppose that as it is presented in Fig 2 (b), the established link between nodes F and G which functions in channel 6 is broken due to any unexpected reason, such as the existence of high interference in the utilized channel or elimination of line of sight.

Since in the illustrated topology the main objective of using dual radio in each mesh router is attaining higher link throughput, the broken radio in each node attempts to find an alternate path to exploit the available link capacity as much as possible. By means of the latest topology information in each node which is acquired through mesh nodes' broadcast messages, the new redundant paths will be constructed through node pairs (F,C) and (G,H) as it is displayed in Fig 2 (c).

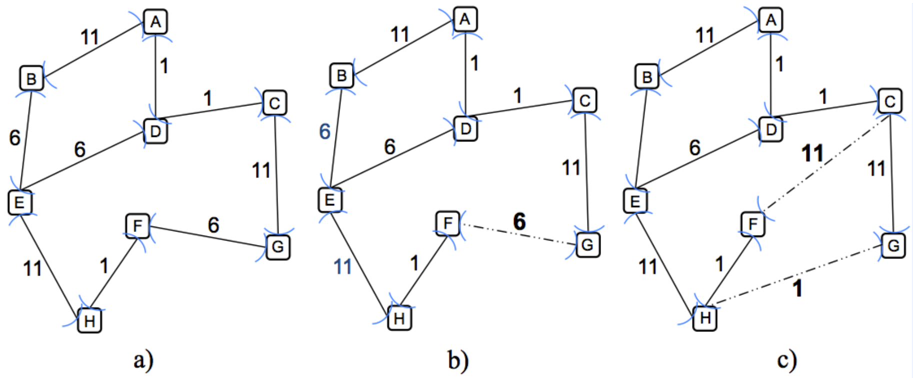

Fig. 2. Functionality of flexible antennas in a sample WMN topology

After determination of the best neighbor, each mesh router requires to change its antenna alignment properly in vertical and horizontal directions to establish a resilient wireless link. Fig. 3 illustrates a practical structure for implementation of the proposed solution within the wireless mesh nodes. Toward deploying a multi-radio multi-channel mesh network, it is recommended each node be equipped with 2 wireless interfaces that each adapter could be connected to a separate directional antenna to radiate in a specific direction. To justify the antenna orientations in appropriate directions, 2 stepper motors are utilized which are being controlled by the implemented algorithm within the mesh router.

In Fig. 3, side and top views of a single mesh node with 2 directional antennas connected to it, are shown. As it is demonstrated, by means of stepper motors, each antenna is able to rotate in clockwise or counterclockwise directions up to 180 degree to find the best succeeding node for passing the network traffic to it. This capability, in addition to the formation of high throughput links and optimizing the amount of consumed energy, will results in the promotion of mesh network stability in the occurrence of any link failure among the mesh nodes. In fact, in this case, the rotating antennas are able to discover another proper neighbor node to create a reliable connection with it based on the predetermined QoS margins by means of QAE module.

One of the most challenging steps of the offered solution is tuning the orientation of directional antennas to cover enough nodes, such that the network topology is preserved; on the other hand, it is necessary to set the antenna to the orientation that the network interference is minimized. This issue is further complicated by the channel assignment, because only the radios in each other's interference range and using the same channel interfere with each other. Through the proposed algorithm, it is attempted to address the whole aforementioned concerns properly to achieve the main goals of the presented architecture.

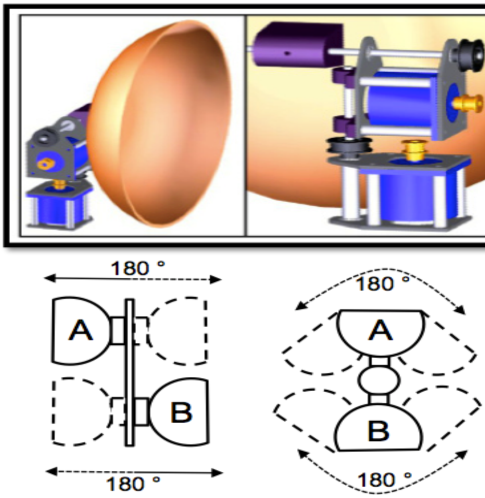

Fig. 3. Flexible antennas with dynamic orientations

Fig. 4 represents the offered algorithm for the operation of each node to attain higher level of energy conservation and throughput. As it is shown, the process continuously monitors the functionality and quality of established links in specific intervals. When initialized timer reaches zero, the link quality will be checked and if

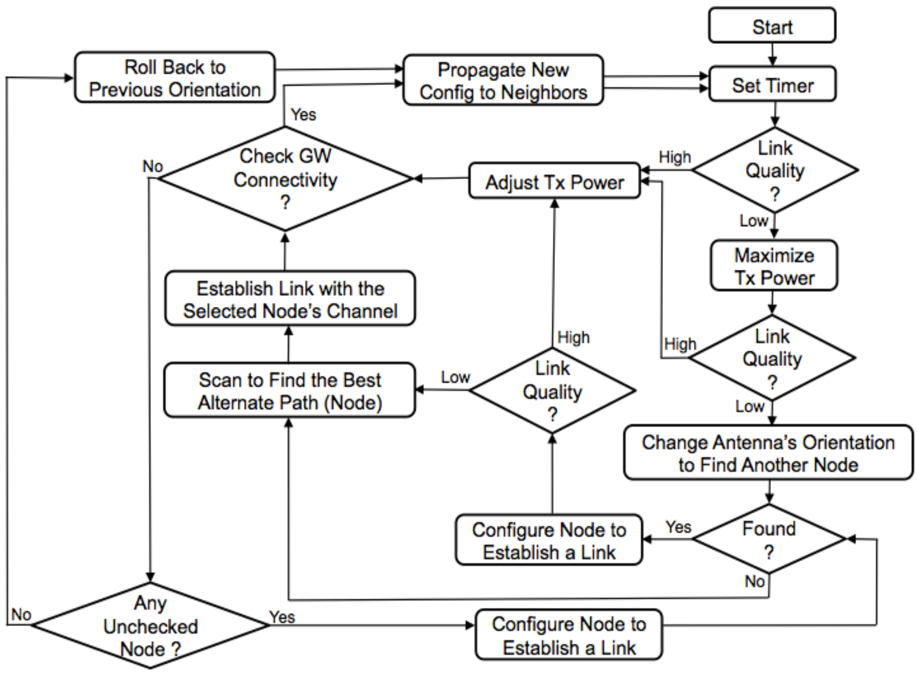

Fig. 4. Proposed algorithm to adjust antenna orientation and TX power

it is less than predetermined thresholds, TX power of the corresponding radio will be maximized. Then, link quality will be rechecked again and if it is elevated, the TX power based on RSSI and receiver sensitivity values of respective adapter will be adjusted to the optimum quantity.

Through checking the gateway connectivity in the next stage will be identified that the applied changes haven't had any undesired effect on the functionality of mesh network. According to this fact that each node broadcasts its latest links' status within the mesh network domain, all nodes have a map of current network topology. If the relevant mesh node couldn't find any peer node to establish a proper wireless connection with it to achieve higher level of QoS, it resumes its previous orientation and waits to make another try in the next time period. In the case that link quality after amplification of TX power to the highest value still is lower than the specified margins, scanning procedure to find another choice to establish more resilient link will be taken place. In the last step of each round in the presented flowchart, the latest node's information will be propagated through the network to inform the others about the recent situation. In the succeeding sections, 2 separate scenarios for evaluating the primary functionalities of offered architecture are expressed and acquired outcomes are delineated in detail.

4 Simulation Setup

To investigate and validate the fundamental operation of offered framework, two elementary scenarios were conducted on multi-radio multi-channel mesh topologies. The main purpose of running these experiments is the correlation of battery lifetime and achievable throughput for various TX powers in each mesh router. In both scenarios, fixed UDP offered load from source node A, is transmitted to node B through directional antennas of intermediate mesh routers that radiate in 5 GHz frequency band.

Table 2. Simulation setup parameters

Simulation Time	300 seconds
Simulation Iteration	10 times
Packet Size	1024 Bytes
CBR for UDP offered load	5.5 Mbps
Utilized Frequency Channels	36, 44, 48, 56
Initial Charge of Battery	1900 J, 6100 J
Node distance	900 m
Channel Bandwidth	20 MHz
Max Transmission Power	25 dBm
Transmission Rate	24 Mbps
Wireless Standard (PHY/MAC)	802.11a
Routing Mechanism	Open11s (802.11s)
Node Distribution	Static
Antenna gain/beamwidth	11 dBi / 120°
Path Loss Model	Friis Free Space

The second experiment is performed in 2 phases; in the first one, such as the first scenario the achievable throughput and battery lifetime are measured for nodes A and B while they are connected to each other by 3 hops. In the next one, it is assumed that the default wireless link that interconnects the node B to the mesh backbone is broken and this node finds an alternate path through its other neighbor node to reach node A.

Respective utilized configurations for the conducted simulation scenarios are mentioned in TABLE II in detail.

5 Results and Discussion

To ground our discussion, we present the obtained results for the first scenario, which its relevant topology is illustrated in Fig. 5. As it is shown in demonstrated graphs in Fig. 7, the remaining battery energy and throughput metrics are quantified in duration of 300 seconds for two different transmission power values. In the second diagram, measured throughput at node B and remained battery energy for both mesh nodes were displayed while the TX power is equal to 25 dBm (~316 mW). By beginning of the simulation, the battery energy of each node starts reducing from its initial value in a linear tension. In the middle of simulation period i.e. 150s, node's B battery is finished and consequently the link throughput value degraded to zero. On the contrary, when

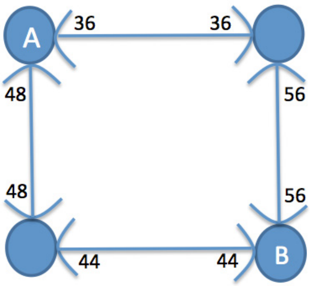

Fig. 5. Multi-radio Multi-channel mesh topology for the first scenario

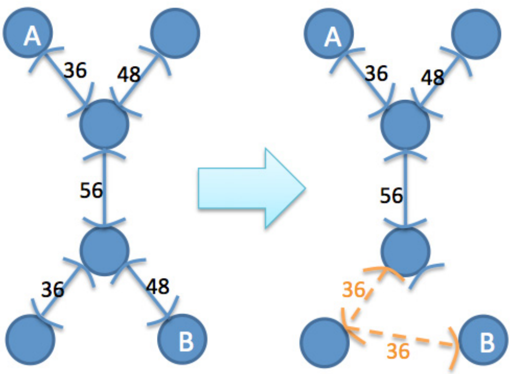

Fig. 6. Topology of second scenario in 2 phases

the TX power is deducted to 20 dBm (~100 mW) as it is presented first graph in Fig. 7, not only at the end of simulation, both nodes still are alive, but also high throughput values between 5.46 and 5.5 Mbps regarding the UDP offered load are attained. In spite of long determined distance (900 m) between paired links in simulation setup, the achievable throughput is almost as equal as the UDP offered load. It is important to note that since the selected transmission rate is assumed 24 Mbps and by using the non-overlapping channels to alleviate the interference impact, the attained throughput in the conducted experiment should be close to 5.5 Mbps offered load value. Acquired throughput quantities, which are presented in Fig. 7, are consistent with this fact.

For the first scenario, in addition to the aforementioned TX powers, similar experiment was directed when the TX power was set to 15 dBm, but the average RSSI in the neighbor nodes respecting the long predetermined distance in the simulation

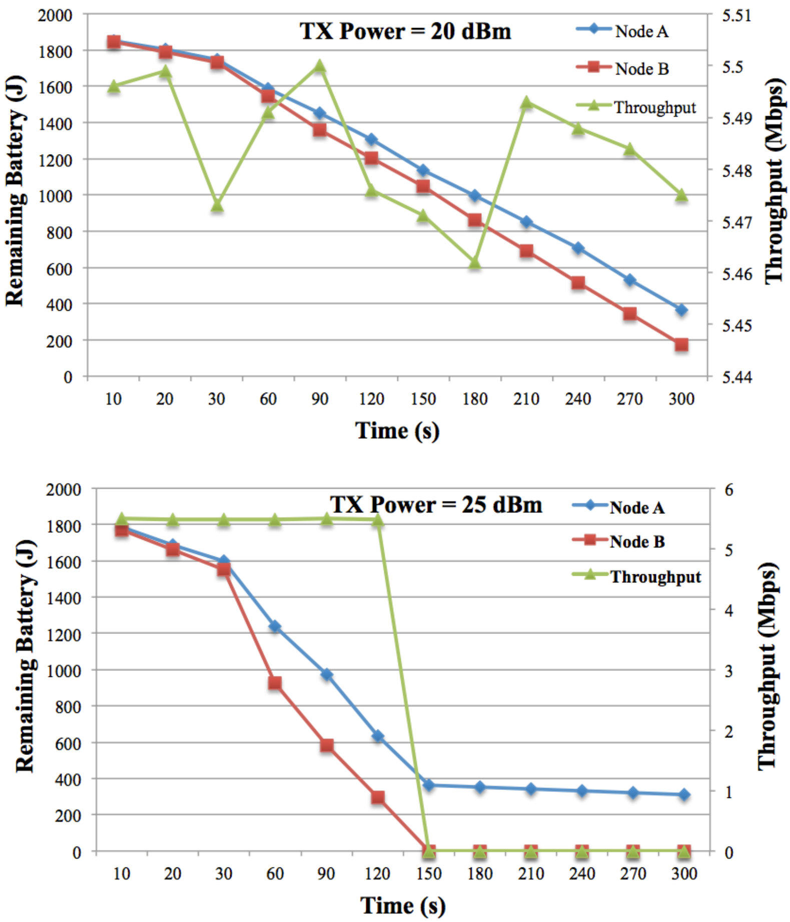

Fig. 7. Acquired results of the first scenario

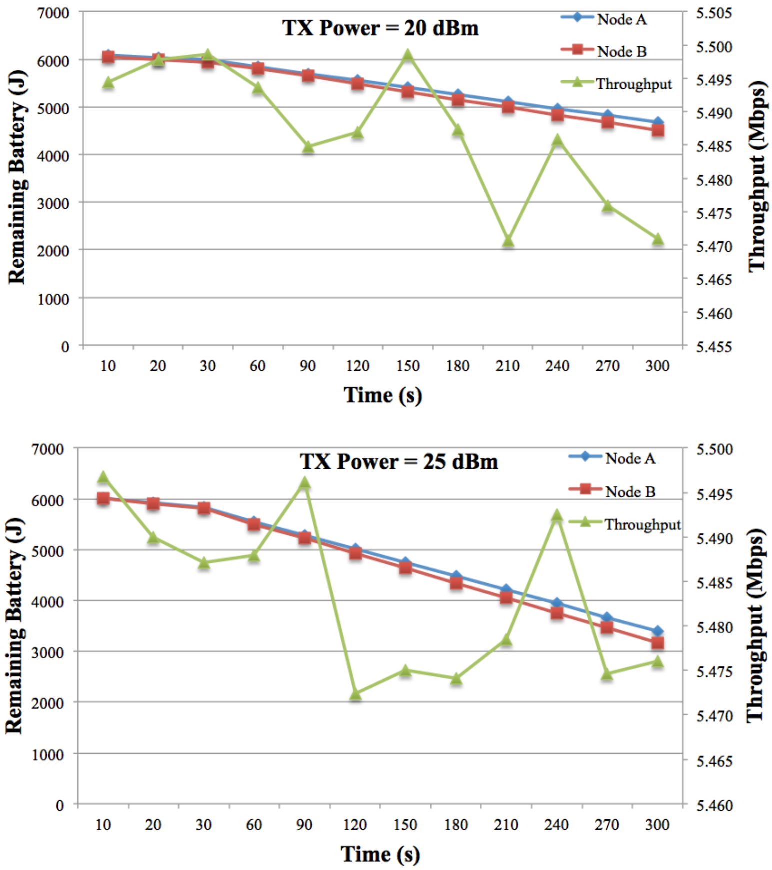

Fig. 8. Acquired results of the second scenario (first phase)

setup, is not strong enough to establish a reliable wireless link. Average quantified RSSI values at node B for TX powers equal to 15, 20 and 25 dBm are respectively -73.15, -63.11 and -60.51 dBm while the defined threshold value to create a reliable wireless link is regarded as -70 dBm. Analogous simulation setting is applied for the second scenario, which is conducted in 2 phases and its topology is illustrated in Fig. 6.

In the first stage, generated UDP traffic at node A, after traversing 3 hops will be delivered to node B. Same performance metrics were quantified at node B when transmission powers are 20 and 25 dBm. Regarding the represented graphs in Fig. 8, by tuning the amount of TX power in each radio of every mesh router, tangible amount of battery charge will be preserved while the link throughput through the whole experiment persists in the proximity of expected value.

To emphasize the importance of TX power optimization process in the offered framework, it is suffice to regard that in Fig. 8, the remaining battery of nodes A and B at the end of the experiment for TX power 20 dBm are 4679 and 4508 J respectively, while for the TX power 25 dBm, remained charge in the nodes' batteries at least 1300 J is less than the former case. In the next phase of second scenario, it is supposed that the wireless link, which was functioning in channel 48, is broken and according to the proposed flowchart, disconnected radio of node B modifies its antenna orientation and channel frequency to establish a reliable link with its nearest neighbor, which is operating in channel 36. Although by this topology change the number of available hops between nodes A and B will be increased, there is not any evident difference between acquired results in conducted phases of this scenario. Also, in addition to the reduction of remaining battery charge in node B in comparison to the previous phase, specific amount of energy should be considered for feeding the stepper motors to change the orientation of respective antenna at this node. With regard to the physical dimension of selected antenna and motor specifications, particular value should be included in the consumed energy at node B which respecting the battery lifetime and stationary position of nodes can be neglected. Fig. 9 demonstrates the obtained results for the second phase of second scenario.

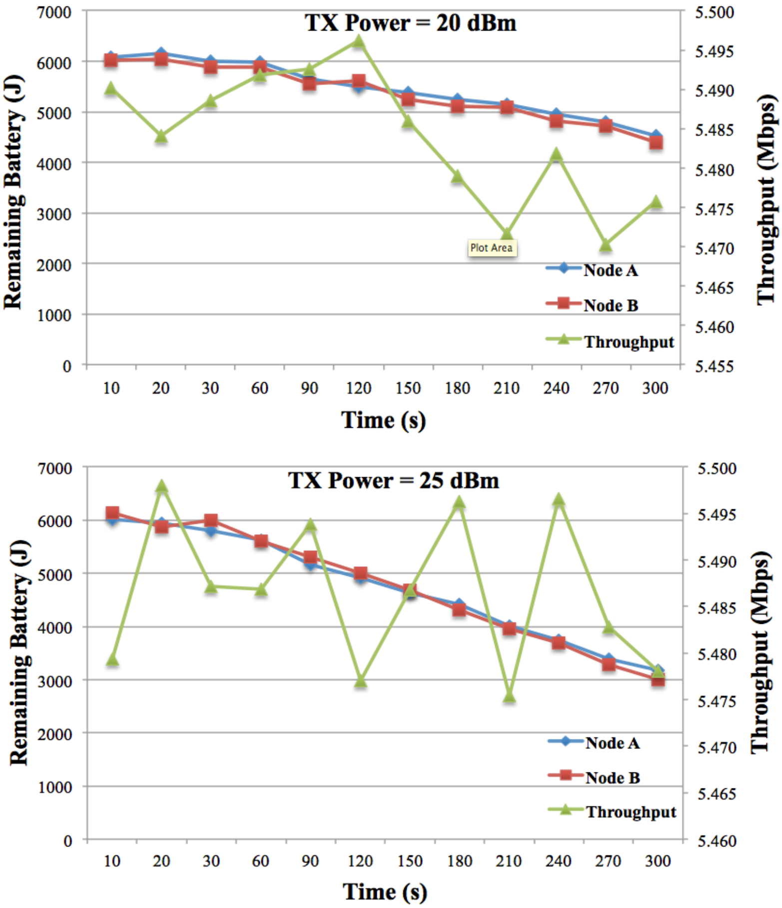

Fig. 9. Acquired results of the second scenario (second phase)

6 Conclusion

As a matter of fact, this study is ended to the findings, which corroborate the outcome of a great deal of the previous works in this field. Actually, the proposed framework for utilization of flexible antennas in the mesh networks not only preserve tangible amount of energy in long term operation of wireless topology, but also alleviate the impact of inter-interference among the utilized nodes through the mesh network. Thus, conducted research equips the scholars with an effective solution to deploy green wireless mesh networks through different geographical locations regarding the promotion of achieved throughput and reduction of power consumption for each mesh router. However, more research on this topic needs to be carried out before the appropriate association of system components is more clearly perceived.

In the future works, we are planning to improve the operation of each component within the proposed architecture and evaluate the system functionality by means of other familiar performance metrics in much more complicated network scenarios and topologies.

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