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A dynamic channel assignment method for multichannel multiradio wireless mesh networks

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Abstract: The popularity of wireless communication accelerates research on new technologies that are required to satisfy users' needs. Wireless mesh networks (WMNs), which are additional access technologies instead of being a renewed one, have an important place among next-generation wireless networks. In particular, the capability of working without any infrastructure is the most outstanding advantage of WMNs. There are many studies aimed at WMNs, particularly channel assignment and routing methods for multichannel multiradio structures that provide higher data capacity. Interference, which has a direct effect on the quality of communication, is still a challenge to be addressed. In this study, multichannel multiradio WMNs and various channel assignment schemes are analyzed. Directional mesh (DMesh) architecture, which uses directional antennas to form a multichannel structure, is analyzed in terms of channel assignment procedure. A new interference-aware channel assignment scheme that aims to eliminate DMesh's disadvantages is proposed and performances of both schemes are compared. Several results of experimental analysis prove that the proposed channel assignment scheme improves the performance of DMesh.

Key words: Wireless mesh networks, channel assignment, interference

1. Introduction

Wireless mesh networks (WMNs) are ad hoc network systems that arise to provide better service infrastructure for next-generation wireless networks. Because of connecting fixed and mobile devices with wireless links, a multihop ad hoc network is obtained. WMNs have properties like quick installation, easy maintenance, low cost, high scalability, and dynamic self-organizing/recovery, which bring WMNs flexible characteristics. One of the most important advantages of WMNs is the ability of overcoming detected failures in the network and making up for the deficiencies of existing ad hoc networks, wireless local area networks (WLANs) and wireless personal area networks (WPANs), in view of the flexibility and connection reliability via multiple transmissions independently from the infrastructure [1]. Other advantages like robustness and reliable service area give them the opportunity to outshine other technologies. Most IT companies have realized the requirement for and profit of mesh systems in the market and have focused on production and development of mesh system parts. Besides these advantages, there are some important points that must be taken into consideration about mesh systems. The presence of a large number of nodes in a mesh network increases the complexity, causes scalability/manageability problems, and makes the network become a target for security threats. With every new application to supply necessities, security and conservation of information become a problem.

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A typical WMN architecture from top to bottom covers three levels: gateways, mesh routers, and mesh clients (Figure 1). Gateways act as a bridge to connect the WMN components to those of other networks

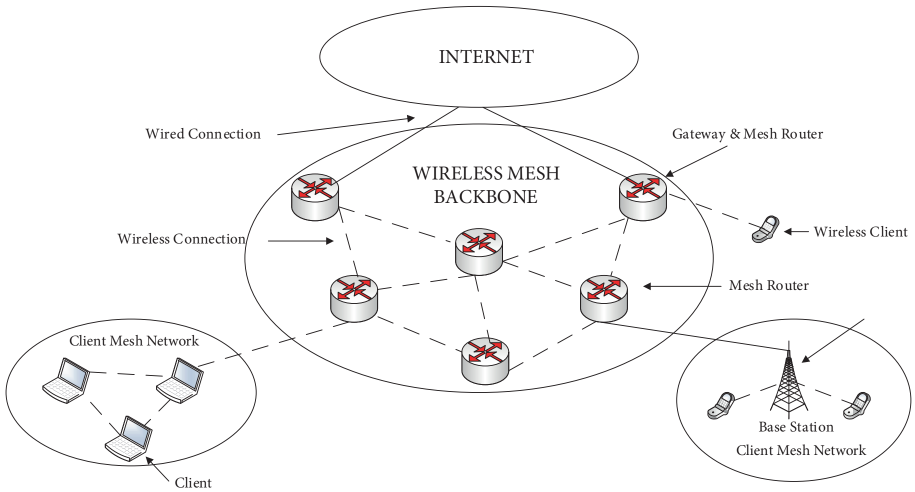


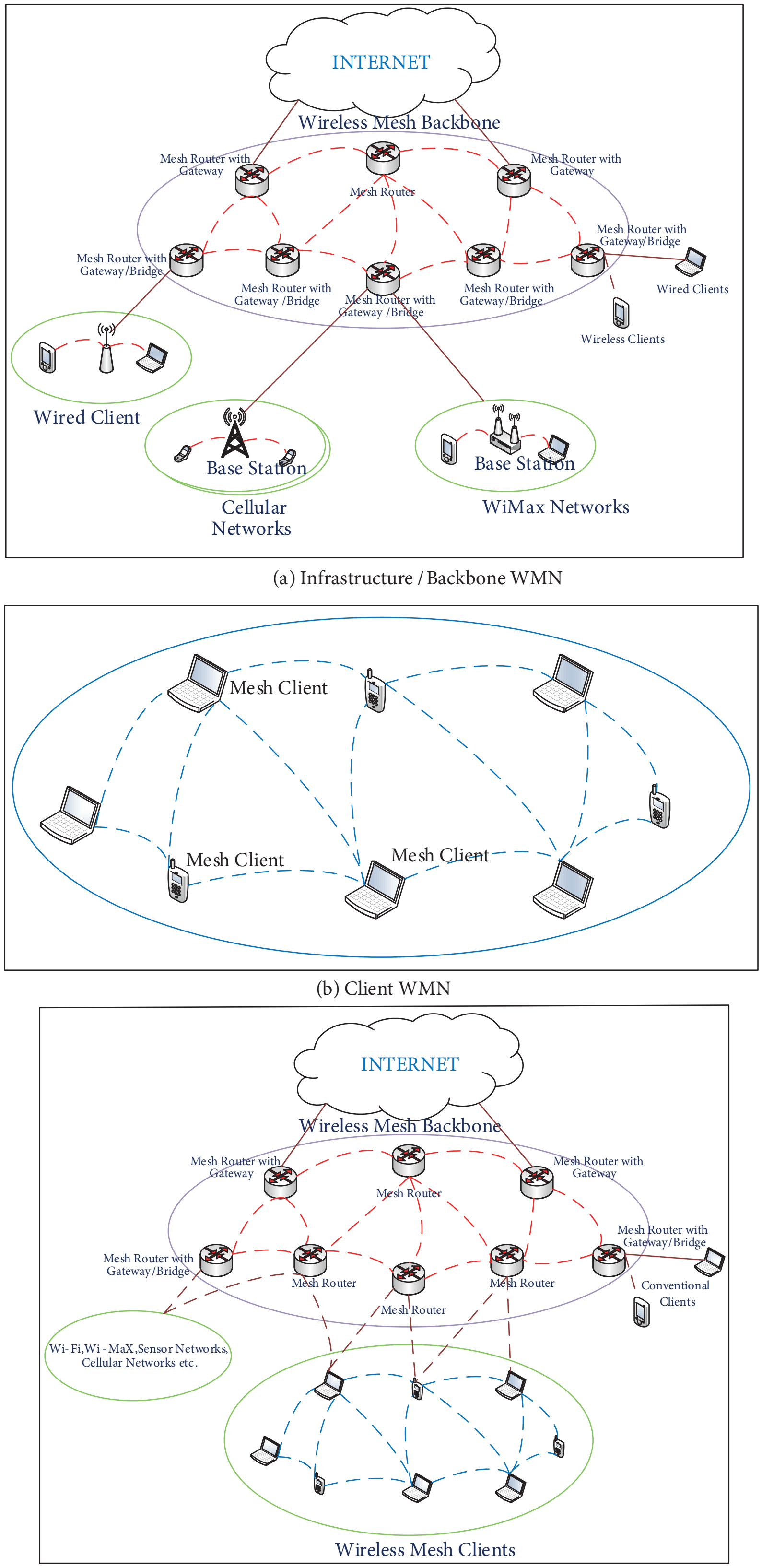
Figure 1. A typical WMN architecture.

like the Internet. Mesh routers transmit/receive packets to/from other WMN components. At the edge of the architecture, there are mesh clients, which contain wireless and fixed devices using the WMN services.

There are three types of WMNs architecture [2] that can be seen in Figure 2. Infrastructure/backbone WMNs are combinations of wired and wireless connections. Their basic topology consists of three layers (shown in Figure 2a): Internet, mesh routers, and mesh clients. The mesh router layer is the core of the topology. This layer connects to the Internet through the Ethernet. The mesh client layer can be formed with various network structures. Clients in this layer can connect to the Internet directly via both mesh routers and the corresponding access point (AP). Client WMNs, shown in Figure 2b, are similar to ad hoc networks in many regards such as APs, capability of working independently of infrastructure, and self-organization feature. No router is required for peer-to-peer connection between mesh clients. They are able to transmit packets to a destination successively through other clients with multihopping. Thus, they must have routing and self-management properties successful packet transmission. Hybrid WMNs consist of infrastructure and client WMNs, as seen in Figure 2c. The infrastructure part provides a connection between the mesh network, Internet, and Wi-Fi and WiMAX networks while the mesh clients are able to organize self-routing operations.

In a wireless mesh network, every router contains multiple network interface cards (NICs) or radio interfaces to make simultaneous transmissions possible. In this way, the network's capacity and throughput increase while decrement in interference level is monitored [3]. Such kinds of structures are called multichannel multiradio WMNs (MC-MR WMNs).

In MC-MR WMNs, every radio is adjusted to work on an orthogonal channel. Two radios can communicate only if they are assigned to the same channel. The 802.11b/g standard supports 3 and the 802.11a standard supports 12 orthogonal channels, which means that channels are limited resources and channel assignment is an important issue for MC-MR WMNs. An efficient allocation of the existing channels between mesh routers (nodes) affects overall network performance directly. The main purposes of channel assignment are to decrease interference between channels by using multiple channels and radios and to guarantee the existence



(a) Infrastructure / Backbone WMN

(b) Client WMN

(c) Hybrid WMN

Figure 2. Types of WMNs.

of the available routes between nodes for transmitting packets. Interference is the most important challenge in the channel assignment process. When two close wireless links are arranged to work on the same channel (frequency), they cannot transmit data simultaneously. Maximizing the throughput is another important goal of channel assignment. In addition to all these, load balancing between channels also must be considered. In light of this information, it can be said that a channel assignment approach must support fault tolerance to provide a self-healing mechanism for a network. It should also interoperate well with the routing scheme to divide traffic between the nodes properly, so that any congestion of the traffic at specific points and accordingly data loss can be prevented.

Directional mesh (DMesh) is the first architecture that uses directional antennas with an omnidirectional antenna to the best of our knowledge. In addition, it has the best performance among the other architectures [4]. It uses multidirectional antennas, which are easy to set up and inexpensive. Usage of multidirectional antennas makes simultaneous communications possible. However, DMesh has some disadvantages that affect its performance negatively. In the DMesh architecture, all nodes and their directional antennas are placed to communicate with each other excellently, but in real-world applications such an installation is not possible. In addition to this, in the channel assignment phase, DMesh's assigning of an unused channel to each new connection causes the channels to be consumed very fast, because the channels are already limited resources. Although DMesh tries to fix the interference problem when it occurs, it does not operate properly when either a few channels or no free channels remain to be assigned.

In this study, we present a new channel assignment (CA) scheme, which aims to minimize the interference while maximizing the throughput for MC-MR WMNs. We choose DMesh as a reference architecture to present our architecture's performance. In our architecture, every node has multiple directional antennas, and locations of nodes and positions of antennas are chosen randomly as in real-world applications. The main difference between DMesh and the proposed architecture is the way that it is used to solve the interference problem. Our CA scheme makes an effort to prevent interference at the beginning while DMesh tries to decrease the interference ratio when it occurs. In the CA process for a new connection, our method uses antenna region information to find the possible neighbors that can cause any interference. We use a sample of MC-MR WMN architecture to evaluate our scheme. Performance evaluation results show that the proposed method is more efficient to prevent interference than DMesh. Because of this, a significant improvement in number of successful transmissions and decreasing of packet drops is observed. In the rest of the paper, related works on CA schemes for MC-MR WMNs are reviewed in Section 2. The proposed CA scheme and the working process of the architecture are described in Section 3. The practical results are given in Section 4. Finally, the conclusions of the study are given in Section 5.

2. Related work

The CA process has great importance in the design of MC-MR WMNs. There are three basic goals of CA. Minimizing interference takes place on the top. Interference is one of the most crucial factors that affect system performance in a negative manner. When two nearby links try to work on the same channel and frequency, they cannot transmit data simultaneously. With MC-MR WMNs where each mesh router is equipped with multiple interfaces, which can work on different channels, this problem can be decreased. Interference can be categorized as cochannel and partially overlapping channel interference. In the case of cochannel interference existence, there are two models to determine whether a transmission is successful: the protocol model and the physical model [5]. In the protocol model, each radio has transmission and interference ranges. Two nodes can communicate only if the destination radio is in the source radio's transmission range while no other nodes within the interference range of the destination radio are transmitting at the same time. The interference range is possibly larger than the transmission range. On the other hand, in the physical model, success of a transmission is measured by the signal-to-noise ratio of the destination node [6]. Suppose that SS_{sd} is the signal strength of the source radio's transmission received at the destination radio, NS_d is the total noise at the destination radio, and SNR_{thresh} is the threshold of signal-to-noise ratio. If $SS_{sd}/NS_d >= SNR_{thresh}$, the destination and source radios can communicate successfully. Although the physical model is more correct because it considers all interference factors including from other outgoing transmissions in the network, the protocol model is simpler and thus is more preferable. The 802.11a standard provides 12 and the 802.11b/g standard just provides 3 orthogonal/nonoverlapping channels, which are separated from each other with 5 channels. Thus, their signals do not overlap each other and they can be used by a neighborhood simultaneously. Physical distance of two wireless links and channel separation both affect interference between links. When the distance is fixed, increasing of channel separation decreases interference level. If channel separation is fixed, then decreasing the distance between links causes an increase in interference. Using partially overlapping channels and nonoverlapping channels together provides efficient utilization of the channel resources and further improvement in network capacity. The second goal of CA is maximizing throughput. By using MC-MR assignment, simultaneous transmissions increase and in parallel overall throughput along the network can be improved. Load balancing is the last goal of CA. It aims to assign channels to nodes efficiently, prevent congestion at specific points, and in this way decrease the interference. Next-generation wireless mobile systems act like union networks, which bring different technologies and services together. Current WMNs with a single radio (SR) that use 802.11-based network interface cards (NICs) are configured to work on a single channel (SC). With SC-SR WMNs, interference caused by neighbor nodes affects system performance adversely. Adapting MAC protocols to WMNs, changing channels on the SR, and using directional antennas are some solutions that are suggested to overcome interference problems [6]. However, directional antennas and adaptive MAC are not practical in wide areas and using multiple channels with SR and accordingly dynamic channel switching can cause a serious time-synchronization problem. On the other hand, equipping every node with multiple radios is a capacity-building approach. WMNs with multiple radios use orthogonal channels to alleviate capacity problem by increasing the total bandwidth of the network while an efficient spectrum distribution throughout the network is achieved. Furthermore, availability of existing hardware makes multiradio solutions attractive in terms of economics. Separation of radios that work at different frequencies and have different hear-sense distances, bandwidth, and fade-out characteristics temporally and spatially provides increment in the network capacity. A WMN node has to share a common channel with every neighbor that it wants to communicate with. However, increment of shared channels used by many neighbor nodes brings interference problems. Efficient channel assignment is the main problem to be solved for minimizing negative impacts of interference caused by a limited number of channels and protecting the connectivity of the network, although mesh nodes with multiple radios have an additive effect on WMN system performance.

In the literature, there are many attempts to get solutions of possible performance problems that occur while assigning channels to radios in different mesh environments. Present CA approaches have been categorized according to different criteria. In [7], CA schemes are classified depending on the network control mechanisms. In the first step, CA schemes are categorized as centralized and distributed. In centralized approaches, there is a central control mechanism by which CA problems can be formulated and solved. Problems being formulated by centralized approaches are divided as graph-based [8–11], network flows [12–14] and network partition [15, 16].

On the other hand, distributed CA approaches allow each node to assign the channels by using their own copy of the CA algorithm. They are categorized depending on their traffic pattern into three classes as in Figure 3: static, dynamic, and hybrid [2, 5].

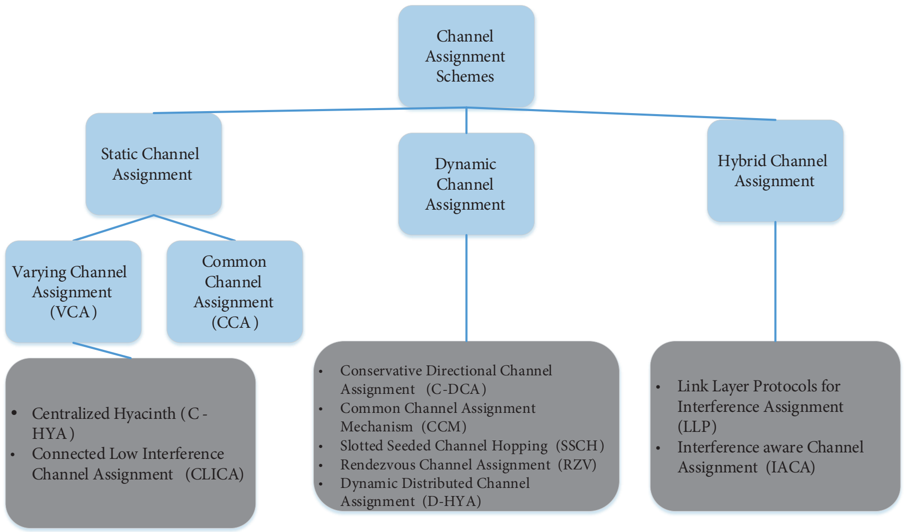


Figure 3. Classification of channel assignment schemes.

In the static approach, each interface of each mesh router is assigned to a channel for a permanent period. The aim of static assignment is maximizing the overall network performance. However, there are some challenges that need to be solved. First, the balance between interference and network connectivity must be satisfied because they are factors that affect each other negatively. When the same channel set is assigned to each node, interference could peak as connectivity drops [16]. Similarly, assigning the same channel set to nodes makes increases in interference and decreases in connectivity level. Consequently, counterbalancing the preservation of connectivity and increasing interference is the main goal of the static approach. Interdependency between channel assignment and routing is another challenge that the static approach faces. Network topology and the bandwidth of every link have effects on the routing process. Beside, network topology and each link's bandwidth demands, which are directly related to channel assignment, are determined when requirements of routing are specified. Therefore, CA processing and routing must work together. Static CA schemes can be classified in two subgroups as common channel assignment (CCA) and varying channel assignment (VCA) [5, 17]. CCA is the simplest CA scheme in the literature. A common channel set is assigned to every radio of each node. The basic advantage of this scheme is associated with the network connectivity since it works like a single channel approach. The throughput of the network can be increased in direct proportion to the number of available channels. However, CCA is still limited by various factors that affect CA in WMNs like balance between number of nonoverlapping channels and number of nodes' radios [5]. Unlike CCA, in VCA, channel sets that are assigned to each interface of the radios can be different. Existence of different channel sets decreases the interference range between adjacent transmissions in some circumstances, but performing the channel assignment process in a planned way is a necessity since poor planning may cause longer paths between mesh nodes [11]. Existing VCA algorithms are centralized channel assignment (C-HYA) [11] and connected low interference channel assignment (CLICA) [18]. C-HYA is a multichannel WMN architecture. The biggest imperfection of C-HYA is based on estimation of the expected total load depending on the load coming from traffic flow, assuming traffic load. The channel assignment method of this algorithm causes multiple transitions over links already visited and makes the time complexity increase since it interconnects traffic patterns with connectivity. In CLICA, a priority value is assigned to every node and channel assignment is performed according to the connectivity and conflict graphs [18]. Although CLICA prevents retransitions over links, the algorithm is weak in terms of flexibility, as traffic patterns of channel assignment for the WMN are not taken into consideration.

The dynamic channel assignment approach relies on assigning any channel to any interface of a node. The related interfaces of nodes must be assigned to the same channel to communicate, so in this way, channels can be switched frequently to provide connectivity between nodes [5]. In addition, every node should visit a specific common channel at certain intervals to discuss the details of the channel that will be used in the next transmission step [19]. Dynamic approaches are subdivided according to the coordination mechanisms used [5]. The common aims of all are providing load balance between links and improving the throughput. D-HYA [20] is a dynamic and distributed CA algorithm, which is based on Hyacinth architecture. In D-HYA, every gateway is thought of as the root of a spanning tree. All remaining nodes are configured as members of a tree. The selected interface of a node is assigned to a channel to communicate with a neighbor node. In this scheme, all possible links between nodes and tree structures must be considered. RZV [21] aims to use multiple channels dynamically and improve the throughput. Channels are selected from among currently available channels during packet transmission depending on the agreements between terminal nodes and the density of channels. A common channel is specified to provide time synchronization and called the default channel. Thus, the common channel mechanism (CCM) method, detailed in [21], is provided. Both CCM and RZV aim to increase throughput of the overall system by using one transmitter and receiver for every node. They do not consider interference during packet transmission since they assume channels to be nonoverlapping. The slotted seeded channel hopping (SSCH) scheme [22] is a distributed CA approach. The frequency diversity of this method improves an IEEE 802.11 network's capacity. As a result, time synchronization is no longer a requirement. Conservative directional/channel assignment (C-DCA) is one of the backbones in this work will be studied in detail in Section 3.

In hybrid CA schemes, fixed interfaces of nodes are generally assigned to a control channel when the others are assigned to remaining channels dynamically. Hybrid approaches can benefit from simple coordination methods of static CA and flexibility of dynamic CA at the same time. Hybrid CA schemes are categorized in two subgroups [5] as link layer protocols for interface assignment (LLP) and interference-aware channel assignment (IACA). In the LLP scheme [17], interfaces are classified as fixed and switchable. Fixed interfaces are assigned to specific channels for long durations. On the other hand, assignment of channels to switchable interfaces depends on the traffic load of nonfixed channels and is carried out for short periods. Distributing channels among different fixed channels makes all channels be in use and guarantees connectivity. In [7], IACA, intended to solve the interference problem of WMNs, is proposed. IACA is based on an approach called the multiradio conflict graph (MCG) that builds a conflict graph structure by displaying edges between mesh nodes [17]. Accordingly, a radio of each node is configured to work on a control channel. Thus, a common network connectivity graph is formed. In IACA, the number of interfering nodes, which are apart from the mesh router but work simultaneously and visibly with it, is calculated.

Static and hybrid CA schemes in Figure 3 are beyond the scope of this paper. We do not use any static interface as in static or hybrid CA schemes, and we present interfaces that are used consecutively in between the channels. Thus, the dynamic CA schemes require smaller numbers of interfaces. The dynamic CA method, which is called conservative directional channel assignment (C-DCA), is one of the backbones in this study. We will explain C-DCA in detail in the next section.

3. New interference-aware dynamic channel assignment approach

In this section, an alternative approach to the C-DCA scheme that is used by DMesh architecture [3] is proposed. C-DCA is a dynamic and distributed CA method that aims to increase throughput of MC-MR WMNs. We refer to our proposed architecture as improved DMesh (iDMesh). DMesh combines spatial separation in directional antennas with frequency separation in orthogonal channels. In this way, more transmissions with less interference are achieved. Besides, DMesh benefits from the advantages of practical directional antennas like inexpensiveness and wide beam-forming. There is much work done to improve throughput of MC-MR WMNs in the literature [20, 24]. However, just omnidirectional antennas are used on the routers in these works, which makes the interference levels of the networks increase. That is, the goal of increasing throughput while decreasing interference of CA schemes fails. On the other hand, DMesh overcomes this dilemma with its distributed and dynamic CA scheme (C-DCA). DMesh follows three steps in the CA procedure: compose a physical tree whose roots are gateway nodes, route packets through the network, and perform the CA scheme.

The physical tree composition process occurs in four steps. 1- When a new node (it will be called CHILD) wants to join the tree, it starts listening to host and network association (HNA) messages coming from nearby parent nodes by its omnidirectional antenna that works in single-channel, single-radio mode and it chooses the best parent option according to these messages. 2- The chosen parent (it will be called PARENT) is informed about this choice with a child response message (CRM). PARENT answers this message with a parent response message (PRM). If the PRM is positive, then both PARENT and CHILD nodes set their directional antennas to point at each other. Otherwise, CHILD continues listening to HNA messages coming from other parent nodes. 3- PARENT sends a READY message from the interface that is used to communicate with CHILD to show that it is ready to connect with CHILD. CHILD sends a JOIN message in reply to the READY message positively. CHILD is a member of the tree after this messaging and it starts its own HNA messages as a potential PARENT node. 4- The PARENT node broadcasts a ROUTE-SETUP message that contains the new CHILD node's interface IP through the gateway node recursively after receiving the JOIN message. In this way, it informs all nodes about the CHILD node. In some cases, a CHILD node that makes a decision to change its PARENT based on HNA messages coming from another PARENT node broadcasts a LEAVE message to report this change and old entries are made invalid.

The routing process is called directional optimized link state routing (DOLSR), which is an extended version of OLSR, and obtains multihop routes in single-radio, single-channel omnidirectional mesh networks [4].

C-DCA is found as the most efficient CA algorithm for DMesh [3]. The C-DCA algorithm performs channel assignment in two steps. First, an unused channel is searched. For an X node, an unused channel means a channel that is not used by X or nodes in X's interference cone. If such a channel does not exist, then the least loaded channel is assigned to X. Geometrical calculations can be used to determine which nodes are inside the interference cone. The nodes in interference areas need to know channel usage information of each other and traffic rates of the channels. One of the main problems of C-DCA is ignoring the overload situation of the network. Because all unused channels are assigned at the beginning, in the case that there are no unused channels left, the probability of interference caused by reassignment of already used channels increases. Our proposed method (iDMesh), suggested as an alternative to C-DCA, gives more importance to interference and tries to prevent interference at the beginning. Thus, it decreases interference while it increases throughput of the overall network [19]. iDMesh consists of the same tree-forming and routing steps and message structures as DMesh. On the other hand, it is different in the CA phase. The CA procedure of iDMesh comprises the following steps:

I. The new node-joining network determines the directional antenna's region in which its prospective PARENT node stays with geometrical calculations.

II. The channels already used by the prospective PARENT and its neighbors are removed from the channel selection list.

III. The busy channels in either PARENT or CHILD's sight are also removed from the list.

IV. If there are nodes communicating in the transmission area used for PARENT and CHILD's communication, then the channels used by those nodes are removed from the list.

V. The total number of channels in the channel selection list is checked after every step. If there exists only one channel, the procedure does not move on to the next step and assigns the existing channel.

The antenna region used for transmission between PARENT and CHILD nodes is indicated by using the location information of these nodes. Antenna regions of a node having four directional antennas and angle of deviation are shown in Figure 4.

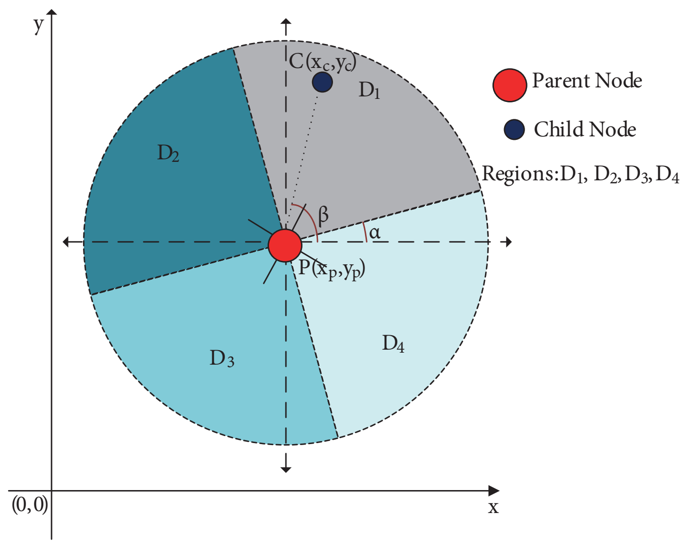


Figure 4. A node with four-directional antenna, the angle of deviation, and communication regions.

In Figure 4, let P with coordinates (x_p, x_y) represent the PARENT node and have four directional antennas. Also, let C be a potential child node willing to connect P with coordinates (x_c, y_c) on the plane. α is the deviation angle of one antenna of P through the plane and is chosen randomly from the angles in $\left[0, \frac{\pi}{2}\right]$ to get simulation results in Section 4.

It is necessary to determine the signal influence area while considering the transmission of each node on the plane and compute the relevant antenna region for a new incoming node. For the computation of regions, we used basic trigonometrical calculations. The angle between two consecutive antennas of a node is $\left[\frac{\pi}{2}\right]$ and the plane angle of each antenna (α) is chosen randomly at the beginning of the simulation.

We make this computation by using α, tracing the regions in a counter-clockwise direction. It can be assumed that there is a line that connects nodes P and C, so the relation between the slope angle of this line (β) and the slope of line can be represented by

$$\tan\beta = \left(\frac{y_c - y_p}{x_c - x_p}\right). \quad (1)$$

If we want to find β, we can write the expression like

$$\beta = \arctan\left(\frac{y_c - y_p}{x_c - x_p}\right). \quad (2)$$

With knowledge of the above calculations, the nodes in D_1 can be computed by

$$y_p < y_c \text{ and } \alpha < \arctan\left(\frac{y_c - y_p}{x_c - x_p}\right) < \alpha + \frac{\pi}{2}. \quad (3)$$

A node supporting Eq, (3) with coordinates (x_c, y_c) can communicate over the antenna in region D_1 of P. We make similar computations for the other regions as in Eqs. (4)–(6):

$$x_c < x_p \text{ and } \alpha + \frac{\pi}{2} < \arctan\left(\frac{y_c - y_p}{x_c - x_p}\right) < \alpha + \pi, \quad (4)$$

$$x_p < x_c \text{ and } \alpha + \frac{\pi}{2} < \arctan\left(\frac{y_c - y_p}{x_c - x_p}\right) < \alpha + \pi, \quad (5)$$

$$y_c < y_p \text{ and } \alpha < \arctan\left(\frac{y_c - y_p}{x_c - x_p}\right) < \alpha + \frac{\pi}{2}. \quad (6)$$

4. Evaluation

In this section, we present the simulation results, which compare the CA schemes' performance of DMesh and our proposed method, iDMesh, algorithmically. We composed network architecture as illustrated in Figure 5 and used MATLAB 2011 [25] as the simulation environment.

4.1. Network architecture and parameters

The parameters used for simulation are shown in the Table. The parameters used in the algorithms are the locations of all nodes in the network, the location of the new incoming node and the node information selected by that new node as parent, and for each node a randomly chosen deviation of angle. DMesh and iDMesh have the same tree-forming procedure during the node connection phase as mentioned in Section 3. Thus, while establishing the network, we preferred to handle it in accordance with the computations of a definite and suitable tree form instead of determining the locations of nodes and frequencies randomly. For both DMesh and iDMesh, the same network conditions are used. Total number of gateways, total number of nodes, and total number of usable channels are predetermined at the beginning of the simulation. The location information

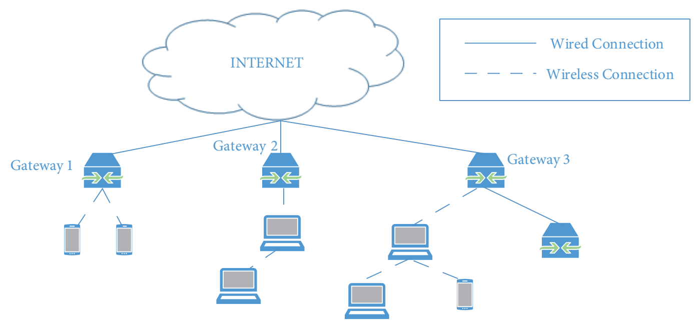


Figure 5. Sample WMN network for simulation.

(coordinates) and deviation angles for each node are selected randomly. After forming the network logically, routing trees were set up according to the selected algorithm (DMesh or iDMesh) and CA was handled.

Table. Simulation parameters.

Simulation area	500 m × 500 m
Number of gateways	Varying between 1 and 20
Number of nodes	Varying between 20 and 100
Number of usable channels	Varying between 3 and 12
Deviation angle of a directional antenna	Chosen randomly in $\left[0, \frac{\pi}{2}\right]$
Traffic model	Poisson
Packet size	1500 bytes
Bit rate	54 Mbps
Simulation time	100 s

4.2. Simulation results

We classify the comparisons of the algorithms based on the effects of number of nodes, usable channels, and gateways in the network in Sections 4.2.1 and 4.2.3. Then we give the call blocking probabilities of both algorithms in Section 4.2.4.

4.2.1. The effect of number of nodes, usable channels, and gateways on the number of transmissions that interfere with each other

We designed four different scenarios with the number of nodes varying between 20 and 200 over an architecture that is composed of one gateway and three usable channels. The effect of increment of the number of nodes on the number of transmissions that interfere with each other is measured for all scenarios. To observe these effects, we changed the number of nodes between 20 and 200 and measured the number of the transmissions that interfered with each other. We obtained the results shown in Figure 6a. Total number of transmissions increases in conjunction with the increment of number of nodes in the network. Because usable channel and gateway numbers are fixed, with this increment the interference rate of the network has a tendency to increase for both DMesh and iDMesh. However, DMesh tries to solve the interference problem when it occurs. On the other hand, our proposed scheme, iDMesh, tries to find all possible conditions when nodes are connected to each other. As a result, iDMesh gives more efficient results in terms of number of transmissions that interfere with each other than DMesh with the increment of number of nodes as seen in Figure 6a. iDMesh yields about 10%-15% amendment for number of transmissions that interfere with each other as compared with DMesh.

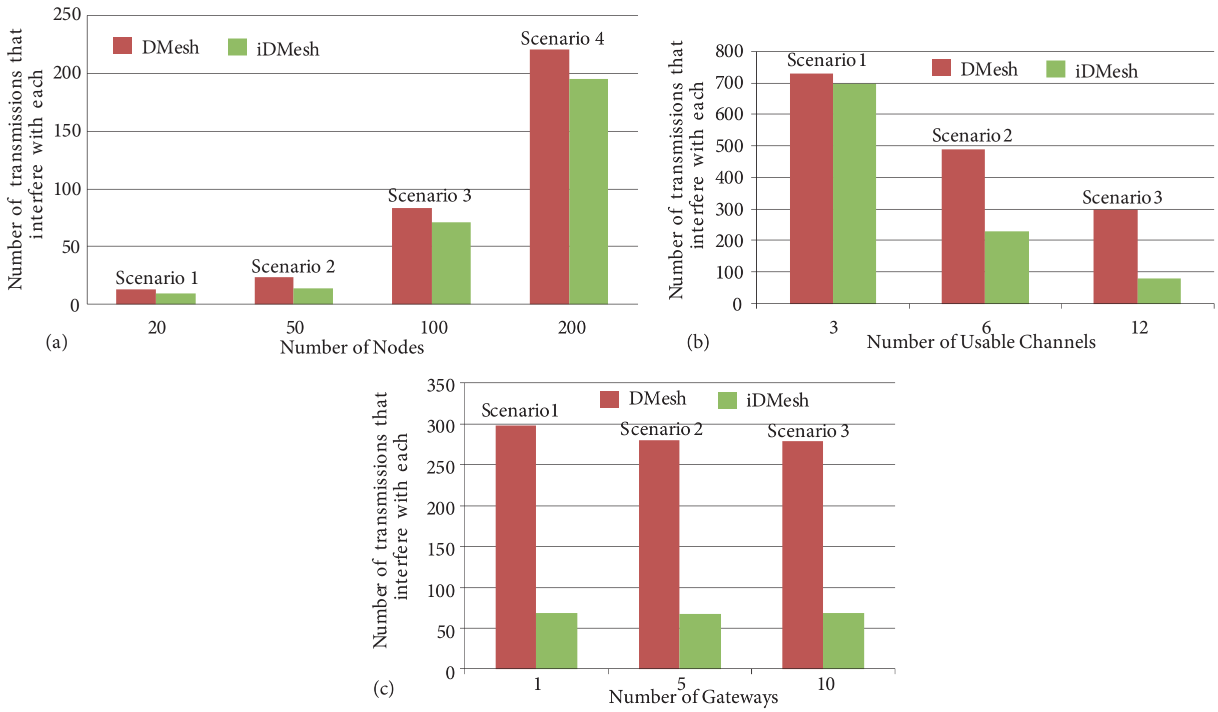


Figure 6. Number of the transmissions that interfere with each other vs. (a) number of nodes, (b) number of usable channels, and (c) number of gateways in the network.

Three different network scenarios with one gateway and 500 nodes were designed while changing the number of usable channels between 3 and 12 to see the effect of the change of usable channel number. Simulation results are as seen in Figure 6b. As seen in Figure 6b, iDMesh has a performance increase of about 75% in comparison with DMesh. iDMesh controls all possibilities that cause interference to assign channels efficiently at the beginning instead of distributing them randomly and this is the primary reason for performance improvement.

Three different scenarios with 12 usable channels, 500 nodes, and gateways whose number changes between 1 and 10 on a network topology were designed to measure the range of the number of transmissions that interfere with each other. We obtained results as in Figure 6c. Increase in the number of gateways causes a decrease in the number of transmissions that interfere with each other for both algorithms. The most important reason for this result is that more gateways allow to distribute a balanced network load and decrease the probability of interference. Again, the prior interference estimation structure of iDMesh makes it better than DMesh. iDMesh has 80% improvement in comparison with DMesh.

4.2.2. The effect of number of usable channels on transmitted and dropped packet numbers depending on traffic density

There are 12 orthogonal channels for IEEE 802.11a and 3 for IEEE 802.11b/g. In light of this information, we produced different scenarios with 50 nodes and 1 gateway to compare performances of DMesh and iDMesh. The scenarios have 3, 6, and 12 channels respectively. The effect of the number of usable channels on the transmitted packet amount in the network is given in Figure 7a while the effect of gateway numbers on packet drops is presented in Figure 7b. Interference occurring between adjacent transmissions is expected to decrease with the increase in number of usable channels. Increase in usable channel numbers results in an increase in successfully transmitted packet numbers for both architectures when DMesh and iDMesh are analyzed on their own. On the other hand, iDMesh gives better performance than DMesh because of the differences between their channel assignment schemes from the viewpoint of interference awareness. As seen in Figure 7a, iDMesh yields 10%-15% improvements in comparison with DMesh for successfully transmitted packet numbers. It is seen that iDMesh has a substantial performance improvement and smaller dropped packet number in comparison with DMesh for identical scenarios in view of traffic density and number of usable channels. Performance improvement is 24% for 3 channels, 160% for 6 channels, and 254% for 12 channels, as seen in Figure 7b.

4.2.3. The effect of number of gateways on transmitted and dropped packet numbers depending on traffic density

We designed three different network scenarios with 50 nodes, 3 usable channels, and number of gateways 1, 5, and 10, respectively, to measure the effect of number of nodes on the transmitted and dropped packet numbers depending on the traffic density. Network data density is changed between 10% and 100% for each scenario and the effect on the transmitted packet numbers is observed according to this change. Results are shown in Figure 8a and 8b. Gateways are the centers where all traffic flow to the Internet is collected. Thus, the more gateways the network has, the more balanced traffic load is among gateways with fewer jams through the network.

4.2.4. Comparison of call blocking probabilities depending on traffic density

Call blocking probability (CBP) is the fraction of time a call request is denied because all channels are busy. We use the Erlang-B formula to calculate CBPs for both DMesh and iDMesh as in [26]. The Erlang-B formula is represented by Eq. (7):

$$P_b = B(E,m) = \frac{\frac{E^m}{m!}}{\sum_{i=0}^{m} \frac{E^i}{i!}}, \tag{7}$$

where P_b is the probability of blocking, m is the number of usable channels, and E is the offered traffic value. E is calculated as in Eq. (8):

$$E = \frac{\textit{Number of successfully transmitted packets}}{\textit{Total number of transmitted packets}}. \tag{8}$$

The impact of traffic density on call blocking probability is seen in Figure 9. We designed three different network scenarios with 50 nodes, 3 gateways, and number of usable channels 3, 6, and 12, respectively, which take the place of m in Eq. (7).

The effect of the number of channels on CBP in the network is seen in Figure 9. The increase in the number of usable channels decreases CBP; in other words, more packets arrive at their destinations successfully when DMesh and iDMesh are analyzed independently. When DMesh and iDMesh are compared, they have almost the same CBP values in the 3-channel scenario with the same traffic density. However, iDMesh gets better results than DMesh with the increase in usable channel number. The main reason for this is iDMesh's successful interference-aware channel assignment procedure that minimizes congestions and packet retransmissions through the network and correspondingly makes more packets arrive at destinations successfully.

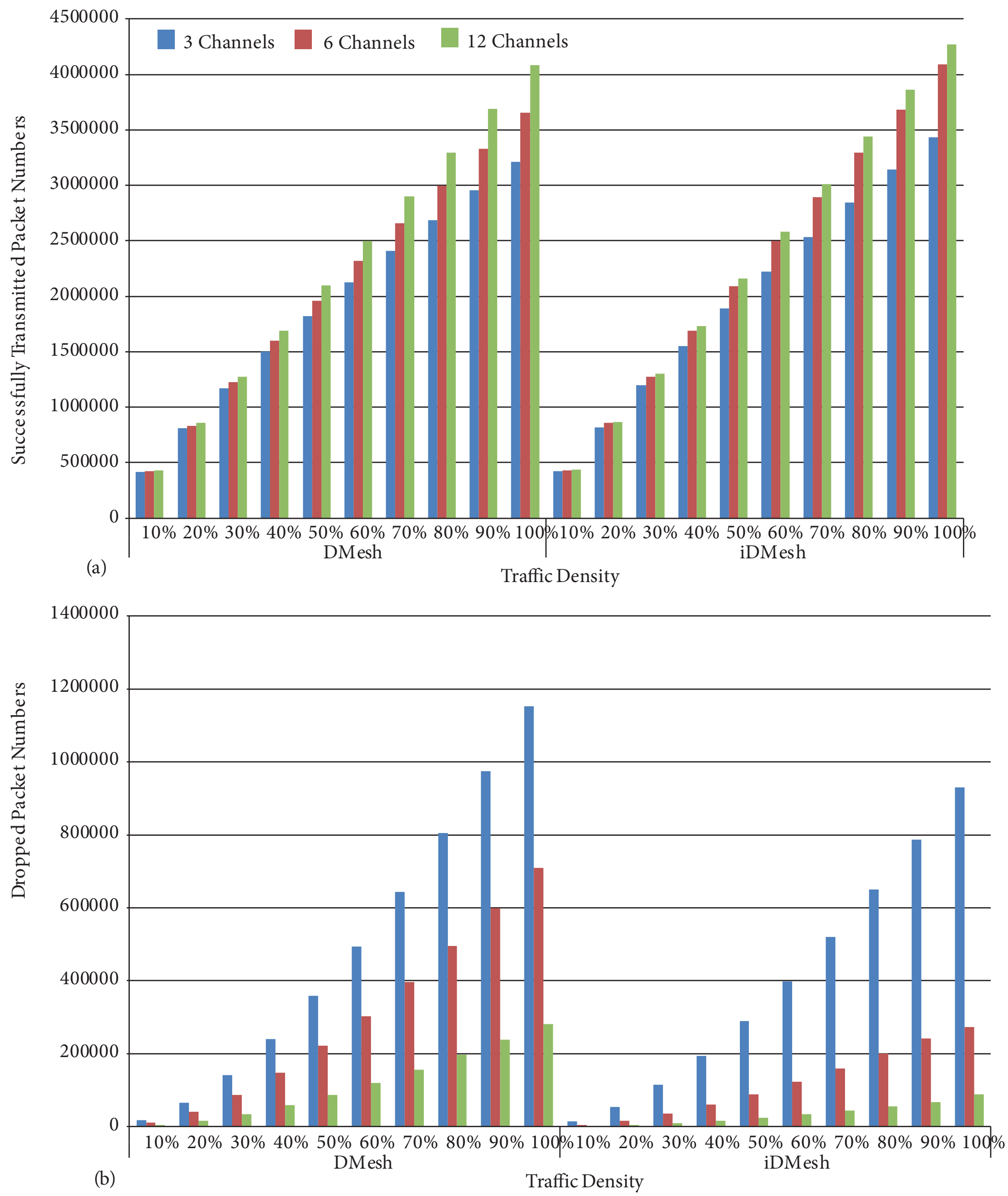


Figure 7. (a) Successfully transmitted and (b) dropped packet numbers vs. traffic density depending on the number of usable channels in the network.

5. Conclusion

The Internet became a part of our daily life with its wide usage areas from banking transactions to online entertainment. Next-generation Internet access is expected to be wireless, like services we use on cellular phones. However, a new network is needed to be designed, the current network system must be improved, or many changes in infrastructure are required to achieve this. Mesh networks solve all of these problems without a need for new infrastructure and they promise more advanced Internet access to users.

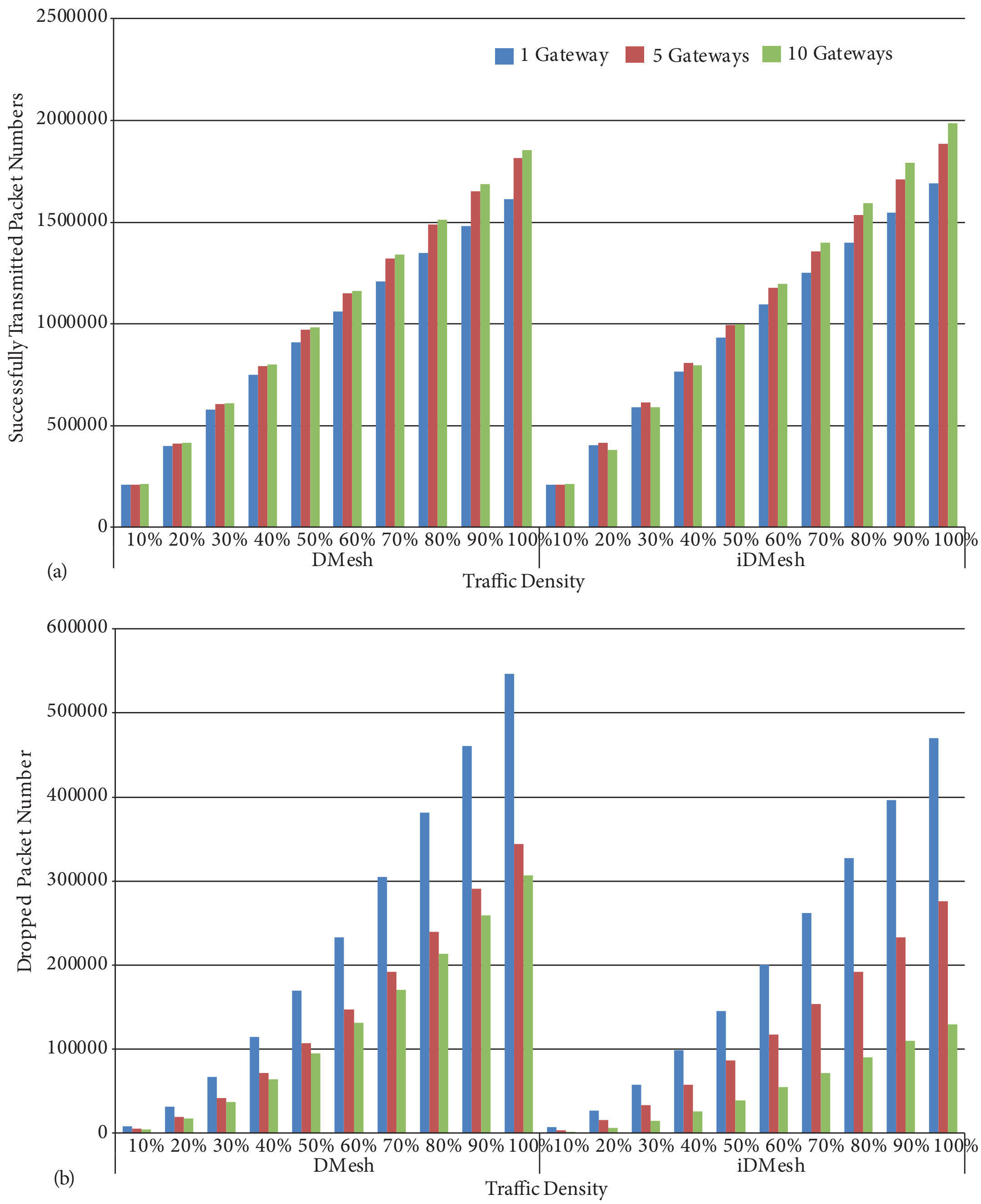


Figure 8. (a) Successfully transmitted and (b) dropped packet numbers vs. traffic density depending on the number of gateways in the network.

DMesh is the first architecture in which a single node uses multiple directional antennas with an omnidirectional antenna to increase network throughput. However, some deficiencies of DMesh architecture design make it show a lower performance. Its channel assignment algorithm tries to find and assign a free channel for each new node. It works perfectly at low packet traffic densities, although when the traffic becomes heavy, the interference ratio starts to increase. In addition, the algorithm assumes that all antennas see each other completely, but this is not possible in practice. Additionally, the nodes and antennas are placed manually to

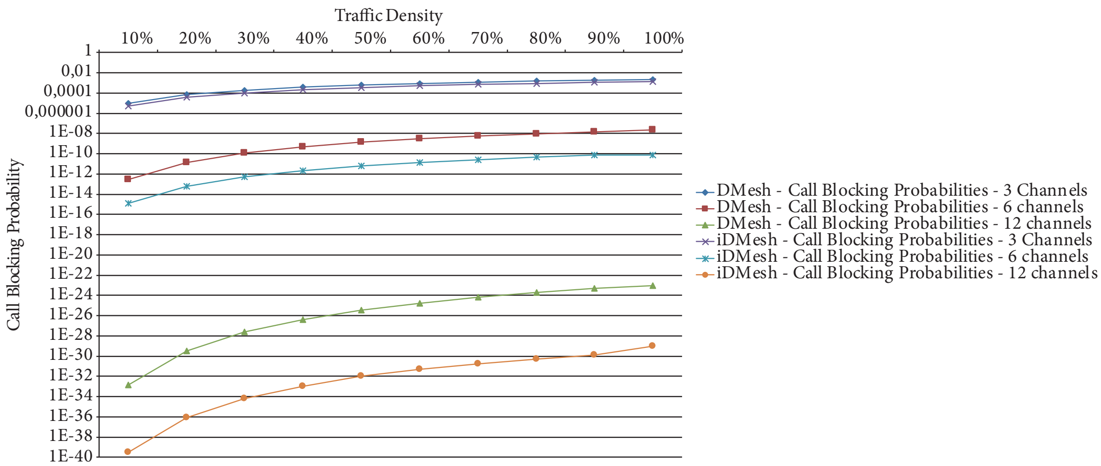


Figure 9. Call blocking probabilities vs. traffic density depending on the usable channel numbers.

be able to provide whole conditions. This approach is also not practical for real applications. In this work, all of these advantages and disadvantages of DMesh are considered and a new interference-aware channel assignment algorithm, called iDMesh, is designed to eliminate all possible interference. A more realistic network environment in which all node locations and antenna angles are chosen randomly is also taken into account. We benefited from inverse trigonometric functions to calculate antenna communication regions.

The CA algorithm that iDMesh uses tries to find all possible interferences at the beginning and assigns channels according to this information to minimize the interference, while DMesh assigns all usable channels at the beginning and does not consider possible interference in the routing tree generation phase. As a result, iDMesh is more effective against increasing traffic density than DMesh for the same channel numbers. The simulation results of this study show that the proposed CA scheme provides significant improvements for DMesh with dynamic parameters such as traffic density and packet numbers. The location detection feature of iDMesh minimizes total system interference and prevents data losses.

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