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The development of green wireless mesh network: A survey

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Abstract

Wireless mesh network (WMN) is a type of self-healing, self-configuration, and peer-to-peer wireless network. Without expensive and fixed base stations, WMN can be established fast, easily, and flexibly at a low cost. The convenience and flexibility of establishing WMN brings a wide range of applications. The request of high bandwidth, high coverage and high transmission rate can be satisfied. Current research on WMN involves routing, resource allocation, mobility control, security and so on. With the increasing concern of green communication, improving energy efficiency is more and more important nowadays. As energy harvesting can overcome energy constraints and extend the network lifetime, it has attracted the great attention from many researchers when designing network. Further, WMN is an important networking mode in next-generation communication to guarantee the quality of service and reduce the networking complexity. Due to such importance, a survey of the research and development in WMN including the future research direction and opportunities is given in this paper.

Keywords: Green wireless mesh network, energy saving, routing, resource allocation, mobility control, security, machine learning, software-defined networking

INTRODUCTION

Wireless mesh network (WMN) is a low-cost network without fixed base stations, and it is self-healing with high robustness. Due to the mesh networking mode, when a mesh node is failed or broken to forward data, alternative nodes and paths will be discovered to guarantee the communication. The single point of failure problem will be solved. WMN consists of mesh routers and mesh clients. Mesh routers always have multiple interfaces, with more energy capacity, while mesh clients often have only one interface, with very limited energy. The mobility of mesh clients is higher than that of mesh routers. For example, smartphones, laptops, unmanned aerial vehicles and so on can be mesh clients, and domestic access routers can be mesh routers[1]. WMN is categorized into 3 types: infrastructure WMN, client WMN and hybrid WMN[2]:

• Mesh routers compose the infrastructure WMN. In infrastructure WMN, mesh clients can only access mesh routers by one hop to complete communication.

• Client WMN is very similar to the pure ad hoc network, which is composed by mesh clients. In this case, mesh clients can communicate directly with each other without accessing mesh routers.

• Hybrid WMN is combined by infrastructure WMN and client WMN. With the most flexible networking mode, hybrid WMN has the potential to be applied in many different scenes.

WMN can make heterogeneous devices cooperate with each other. Different types of networks like cellular network, WiMAX, vehicular network, Internet of things, sensor network and so on can be cooperative with each other through WMN. The access points of different networks can become the mesh routers of WMN. The data traffic can be from a mesh node to the Internet through the gateway or from a mesh node to another mesh node. The traffic flows and network topology are very flexible to satisfy the communication requests. Most traffic flows from source to destination need to be forwarded through multiple hops. The coverage will be extended to make it possible for remote nodes to access the Internet without increasing the transmission power[3]. However, interference will be caused by the feature of multiple hops. Multi-hop communication brings more complicated relationships among mesh nodes. The links using the same wireless channel within the interference range will be interfered mutually. Especially in next-generation wireless communication, the number of devices will increase dramatically and the network density will be very high. Therefore, the network performance decrease like packet loss resulting from interference should be considered and addressed carefully[4]. The wireless resources like channels and spectrum need to be used sufficiently and effectively. The objective of network deployment is to transmit most data by using the least resource.

In addition to the wireless resources, energy is another important aspect and resource which should be consumed efficiently. With the development of green communication, saving energy has become a more and more important and critical issue[5]. Some devices like sensors and smartphones have very limited energy. Once the energy is run out of, the device cannot be used anymore and it will become a dead node. With more and more dead nodes appearing, the connection of network will decrease and some nodes may even become isolated nodes. To avoid this circumstance, energy should be consumed in balance. Further, energy harvesting (EH) which can overcome energy constraints has attracted many researchers' attention these years[6]. Mesh nodes can obtain energy from solar, wind, radio frequency signals and so on. With the ability of obtaining and saving energy, network lifetime can be extended.

As WMN is flexible with low cost, it is an important networking mode in next-generation wireless communication. It can be established in some rural areas where it is hard to build expensive base stations. In addition, WMN can also be used in military and emergency communication due to the flexible topology. In Internet of things, many devices have a very limited transmission range, so WMN can help complete communication by multiple hops. As WMN plays an important role in wireless communication, it is essential to deploy WMN efficiently by considering its characteristics. The network deployment which can improve network performance includes many research areas like routing, resource allocation, mobility control, security, energy saving, *etc*. The detailed recent research is given in Section 2 below. Then the future research opportunities and technologies are provided in Section 3. Conclusions and challenges are summarized in Section 4.

CURRENT RESEARCH IN WMN

Current research in WMN focuses on different aspects. In the development process of WMN, routing, resource allocation, mobility control, and security are important areas all the time. Recently, energy saving has become a more and more heated topic with the development of green communication. Detailed works in WMN are given as follows.

Routing design

Routing is always one of the most important aspects in network design because different route selections will bring different network performance. According to the route establishing time, routing can be categorized into proactive[7], reactive[8] and hybrid routing[9]. Proactive routing methods actively discover and maintain routes all the time. When there is a communication request, less responding delay will be obtained because routes are already known. However, the control overhead is large. Reactive routing methods only start to find routes when nodes need to start communication and transmit packets. The control overhead is less as control packets do not need to be transmitted all the time. Hybrid routing combines the proactive and reactive routing, and different routing methods can be used among different types of nodes. According to the features of mesh routers and mesh clients, proactive routing is suitable for static mesh routers and reactive routing can work well for mobile mesh clients.

The proactive routing can be formulated as an optimization problem, which can be addressed and supported by software-defined networking (SDN) technology with global network view[10]. The objective is the metric to evaluate the performance of routes. Considering different requests of Quality of Service (QoS), different aspects like Expected Transmission Time (ETT)[11], Expected Transmission Count (ETX)[12], throughput[13], packet error ratio[14], energy consumption[15], hop count[16] and so on can be considered. When solving the established routing optimization problem, genetic algorithm (GA)[11], particle swarm optimization[17], multi-objective differential evolution (MODE)[18], ant colony optimization (ACO)[19], reinforcement learning[20,21], fuzzy logic[22,23], *etc*. can be used.

To adapt to the features of mobile mesh clients, most designed routing methods for WMN are reactive routing. When design routing metric, factors which will influence network performance like delay[24,25], load[26,27], congestion[28], interference[4,29], mobility[30], security[31,32], stability[33], and energy[34] can be considered. As the factors can influence one another, more than one factor like delay, intra- and inter-flow interference can be considered at the same time[35]. When the delay cannot meet the threshold request, transmission rate and power will be reduced. ETX and ETT are often used as the basis of many researches. In addition to ETX, available bandwidth and channel diversity are considered in[25]. With larger retransmission times, the energy consumption will be higher[36]. Besides ETT[27], considers load condition and interference. For the routing mechanism, some research considers the flooding control of control packets. AODV-DF[37] reduces the number of route request (RREQ) packets and controls the flooding effectively. More wireless resources can be used to serve the data packets rather than control packets, and load will be reduced.

However, the research of hybrid routing is much less. HMesh[38] combines the proactive routing protocol OLSR[39] and reactive routing protocol AODV[40]. OLSR is used among mesh routers, and AODV is used among mesh clients. HDV[41] uses tree-based proactive routing between mesh routers and gateway, to set reactive routing among mesh clients. Hop count is the only factor considered in routing metric of both HMesh and HDV. CHRP[42] improves the routing metric, considering interference, channel condition and energy of mesh clients. The access process is neglected, and the mesh router which can response route reply (RREP) to the mesh client will be accessed unconditionally. To consider the load condition of the access mesh routers, LA-CHRP[43] selects the mesh router with less load as the access node. However, the condition of the whole proactive path and the regional condition are neglected. RCA-HRP[44] considers and evaluates the condition of whole proactive path. In addition, the regional information like load, speed and energy is considered.

Resource allocation

As wireless resource is limited, effective resource allocation is very important. Channel allocation[45,46] and rate allocation[47] can maximize network throughput and fairness. The relationship between topology and the available number of channels which can be assigned is given in[45]. Different factors and network design areas jointly influence network performance, so many works jointly consider different areas as a whole. Channel assignment and routing can be designed jointly[48]. Routing is designed after channel allocation. The derived outage probability is used to determine the constraint of energy consumption. When considering routing, channel allocation and rate scheduling at the same time, Lagrange duality method can be used to convert the corresponding convex optimal solution into 3 simple sub-problems[49]. Channel allocation and scheduling can be implemented cooperatively[50]. When channels are allocated, loss, interference and channel busy level are considered. In scheduling of sending interface, longer switch interval is given for busy interface with long queue. Jointly allocating resources according to different requests can bring better whole network performance.

With the support of edge computing, more computing devices and resources are provided. As a result, the burden and load via the distributed cloud are then reduced, and the response time can be significantly shortened. WMN can be deployed to bring a new paradigm to enable distributed intelligence[51], and the research on resource and task allocation is more and more heated[52]. Computing capacity, computing delay and transmission delay should be considered to select the best place to offload tasks[53].

Mobility control

Mobility will bring flexible and changeable network topology, which will influence network performance. To reproduce the movement features is the main purpose of the mobility model[54]. Clustering and region division are effective to control mobility and distinguish features of different nodes[20]. Then traffic transmission can be completed based on clusters. A cluster-based network has better scalability, and nodes will be classified into cluster heads, cluster members and gateways. The technology of clustering makes the deployment of large-scale WMN possible[55]. The nodes with similar mobility features can be classified into one cluster because their neighborhood relationship is relatively stable. Therefore, clusters do not need to be established frequently, which guarantees the stable communication. After being clustered, the cost of maintaining the network condition is reduced because the gateways only need to maintain the information of cluster heads and the condition of cluster members is monitored by cluster heads.

With the fast development of wireless mobile communication, more and more mobile devices need to access the Internet. As a result, the density of a network is high, and it will be more and more difficult to control the network. Clustering is also a good way to serve the traffic in dense network[56]. To save the energy of mobile devices, the node with enough energy can be selected as the cluster head to help support the communication among cluster members. The cluster heads can also be selected according to the load, capacity, location and node degree[57-59].

Security

There are different attacks on different Open System Interconnection layers. To avoid and reduce the impact of attacks on the network performance, intrusion prevention, detection and response mechanisms should be designed according to service requests[60]. At physical layer, collision jamming and device tampering may occur. At Medium Access Control layer, passive eavesdropping and jamming attack will decrease the traffic transmission rate. At network layer, black hole, gray hole, worm hole attacks[61], flooding attacks[62], and replay attacks[63] can bring failed data transmission. Flooding and desynchronization attacks can occur at transport layer. The application layer has security risks including logic errors and buffer overflows. The security threats can be generally classified into passive and active attacks. In passive attack, network operation will not be disrupted because the attackers monitor and capture data without triggering real actions. However, the passive attack can be a preparation for active attack. After monitoring and analyzing the network traffic data, the active attack can be done to control and disrupt the normal network operation. The attackers will try to inject, delete or alter data, so the successful transmission rate and network performance will decrease.

It is essential to detect and prevent the damage of attacks on the network. Attacks can be detected by calculating neighbor list and directional neighbor list of the source node[64]. Then the location of the attack and influenced nodes can be provided. Reputation model based on forwarding success and failure rates can also evaluate the nodes' behavior and it is beneficial to study the social relationship among nodes. Then groups with similar status are established. The nodes with weak social relationship may be the malicious nodes and they should be avoided being used to forward traffic[65]. The trust of nodes can also be calculated by using probability theory and packets can be routed according to fuzzy set theory[66]. The network factors like hop count, reliability and link capacity can be considered.

Energy saving

With the development of green computing and green communication, saving energy is an urgent duty to be completed nowadays, so it has become an emergent and important research topic in WMN recently. Energy should be carefully considered when implementing network design. The mode switch between sleep and active can help save energy[67]. To save energy, minimizing the energy consumption[68] or maximizing lifetime[69,70] can be the objective, and EH can be used to obtain energy. Energy will be consumed at different states: monitoring, processing, communication, and state transferring[71]. Four actions that are keeping sleeping, turning on collection, turning on processing and turning on transmission can be selected[72]. Interfaces can be turned on or off according to the energy and selected paths in[48]. When the obtained energy is more than consumed energy, the energy will be saved. Otherwise, the battery energy will be consumed. Besides energy, other factors like delay[73], throughput[72] and transmission rate[74] can also be considered together. The flooding control can be done to change the probability of forwarding control packets like RREQ to save energy[69,75]. When designing routing, few works consider EH. DEARER[74] proposes a cluster-based routing to select cluster head effectively. Energy efficiency and transmission rate are considered, but load and interference are overlooked. The method in[76] minimizes delay, and considers power allocation, tree-based routing and scheduling, which solves the near-far problem. However, interference is still not considered, and it only uses the free-space loss model to describe large scale fading.

Power allocation is another important part which can influence energy condition directly, and it can be done according to the user distribution and predictive EH model[77]. To predict user density in future, the model based on Markov chain can be used. In addition, Gaussian distribution model is used to predict harvested energy. Power will then be allocated according to the energy level. Power can also be jointly assigned with routing and spectrum allocation by mixed integer linear programming (MILP)[78].

In short, the summary of representative studies for WMN is given in Table 1.

OPPORTUNITIES AND TECHNOLOGIES IN FUTURE RESEARCH

With the features of flexibility, low cost, scalability, multiple hops and so on, WMN will also play an important role in next-generation communication. With the fast grow and development of Internet of Things (IoT), WMN can well integrate with and enhance IoT[79]. The coverage will be extended and energy will be saved by the support of WMN. With the increasing number of devices, the size and density of WMN will increase. Network deployment needs more intelligent methods to adapt to the complex network conditions. Machine learning (ML) and SDN can bring more opportunities and potentials for WMN.

MACHINE LEARNING FOR SMART WMN

ML is a heated technology which has been successfully used in many areas like image processing, text mining, natural language processing, agent systems, *etc*. The intelligence of ML makes it also adaptive to implement network design for WMN[80].

It is important and beneficial to understand and predict network conditions, which can be done effectively and accurately by ML. With the predicted outcomes, some adjustments can be implemented to adapt to the varying network conditions. The batch ML needs large amounts of data, and cannot be updated quickly and efficiently after training. Therefore, online or real-time ML which requests less data processing at a time can be used to predict link quality with less computing cost and time[81]. When multiple bands and channels are available at relay nodes, it is essential to select the one with best quality. The channel quality can be predicted by ML and the smarter channel selection methods based on the ML outcomes can be developed to enable larger network throughput and shorter delay[3,82].

Besides prediction, ML can also be used in routing, resource allocation and strategy deployment, and reinforcement learning like Q learning is a very effective method to suit flexible network without a known transition model[80]. It can also solve multi-objective problems for convex or non-convex problems[83]. Reward function is set according to the QoS request like load, transmission rate, delay, distance, mobility and energy[84-87]. The transmission rate can then be adjusted based on the network capacity and quality of experience[88]. The tradeoff between exploitation and exploration needs to be balanced. The exploitation is to use the current best solution, and the exploration is to find more potential and future best solutions. The problem may converge to local optimal solution if exploitation is too focused. Otherwise, the problem cannot converge if exploration is too focused. ε-greedy and soft-max methods are often used to balance exploitation and exploration. Deep learning is also an effective way to learn and control network in real time. Traditional routing protocols may even be removed and replaced by deep reinforcement or other self-learning technologies in future[89]. Past mistakes causing congestion and network performance decrease will be learnt to avoid the same mistakes in future. The structures like convolutional neural network[89] and deep belief architecture[90] can be used. The combination of reinforcement learning and deep learning can make use of the advantages of them together. Results and selections can be achieved automatically in any large-scale network with a lot of states and actions. Real-time traffic will be controlled efficiently[91]. Non-linear, complex and multiple-dimension problems can be solved successfully[92].

Further, with the help of ML, the effects and uncertainties of human element and idiosyncrasy on the development of green WMN can be reduced. The human behavior is not entirely rational and relies on

Table 1. Review of representative studies for WMN

Ref.	Considering aspects									Network performance factors	Methods
		Resource allocation									
	Routing	Channel allocation	Scheduling	Rate adaptation	Power control	Task allocation	Mobility	Energy saving	Security		
Mahmood *et al.*[11]	√									ETT, hop count	GA
Murugeswari *et al.*[12]	√									ETX, delay	Multi-objective evolutionary algorithm
Bokhari *et al.*[19]	√									Interference, delay	ACO
Yadav *et al.*[22]	√						√	√		Delay, bandwidth	Fuzzy logic
Chai *et al.*[43]	√							√		Load, energy	Hybrid routing
Avallone *et al.*[48]	√	√						√		Energy, outage probability	Heuristic, linear programming
Deng *et al.*[50]		√	√							Throughput, load, delay	Huffman tree
Suto *et al.*[77]					√			√		User distribution	Markov chain prediction
Liu *et al.*[52]						√				Delay, cost (computing, storage, data transmission)	Prediction-based online algorithm
Tang *et al.*[47]		√		√						Throughput, fairness	Linear programming, convex optimization
Ramakrishnan *et al.*[54]	√						√			Throughput	Clustering
Li *et al.*[20]	√						√			Delay, hop count, delivery ratio	Reinforcement learning
Kassan *et al.*[71]								√		Packet forwarding	Game theory, clustering, EH
Maleki *et al.*[73]	√							√		Delay, energy, channel condition	Reinforcement learning
Dong *et al.*[74]	√							√		Distance, energy, channel	Clustering
Yao *et al.*[76]	√		√		√					Node location, delay, fading, load	EH, Markov decision process
Yu *et al.*[65]	√								√	Neighborhood relationship	Reputation model
Pugalendhi *et al.*[66]	√								√	Packet transmission ratio	Probability theory, fuzzy theory

ETT: Expected transmission time; ETX: expected transmission count; GA: genetic algorithm; ACO: ant colony optimization; EH: energy harvesting.

existing rules and experiences to large extent. Due to the complicated conditions and potential states, it is really hard for human to give best and secure solutions according to the known knowledge. The results, therefore, may not be the expected ones by the engineering design perspective. Therefore, the influence of unreasonable human behavior should be avoided as far as possible. ML can learn from data and implement automatic adaptation, so the uncertainties in human decisions can be reduced by taking advantage of ML. Further evaluation of ML in the real world should be implemented to confirm the effectiveness and usefulness of ML in WMN[93].

Software-defined networking for effective WMN

SDN, which is an approach to network management that enables dynamic, programmatically efficient network configuration, is also an essential technology in next-generation communication with the capability of decoupling data and control planes. The programmability is improved and it will be easy to manage the whole network[94]. SDN can be applied in existing WMN to combine the advantages of centralized control in SDN and low cost in WMN[95-97]. The centralized network controller can provide high computing ability and storage capability. The whole network information can be obtained by the network controller from switches, and strategies are made according to the information[98]. The rules of routing or resource control computed by the controller will be transferred and installed to the nodes in network[99]. The switches can be simpler because they do not need to make decisions anymore and they can just forward data based on the rules computed by the network controller.

Better mobility management, routing and resource allocation can be achieved. The combination of SDN and WMN has better performance than pure WMN[100]. Service requests can be satisfied by simply updating software rather than changing hardware. Current research about SDN in WMN is still rather limited, and the experiments in real platforms are still needed in the future. Besides, SDN and ML can be combined together to make the network more intelligent.

CONCLUSIONS AND CHALLENGES

WMN is an important networking mode which has been researched and developed for many years. It will still play an important role in next-generation communication due to its multi-hop, flexible and low-cost features. Current research on WMN including routing, resource allocation, mobility control, security and energy saving is summarized in this survey. To improve the whole network performance, further research works need to consider different aspects together. To provide the smarter and more effective services in the future, ML and SDN can be integrated with WMN to realize such a goal. ML can intelligently predict network conditions and learn from the environment to find best solutions and avoid mistakes. Besides, the ability of self-adaptation can bring more intelligence and reduce the influence of human behavior on the development of green WMN. SDN makes the network management more flexible, and more complicated tasks can be completed by the network controller.

Devices deployment will be more and more flexible in the future. Any device can join, leave and move at any time, which brings very flexible topology. Topology deployment and node placement will become a challenging area. Different placements will bring different neighborhood and interference relationships. When designing the placement, the number of nodes connected to the access point should be controlled to avoid high congestion. In addition, when there are multiple gateways in the network, the gateway placement and selection are very important for balancing load. The node placement problem can be formulated as a multi-objective problem to satisfy delay, transmission rate, fairness and energy[101,102]. In big-data era, the locations of services are also very important to reduce electricity cost[103]. The topology design of network, services, computing resources, *etc*. are all important for serving traffic with QoS requests.

When evaluating the performance of different ideas and schemes, it should be kept in mind that the environment in the real world is different from simulation platforms. Thus, it is essential to evaluate network performance by experiments in the real world[104] in the future.

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Authors' contributions

Made substantial contributions to methodology, summarization and writing: Chai Y
Provided insightful directions, supervision and did proofreading: Zeng XJ

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