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Multi-Radio Multi-Channel Protocol for Emergency Wireless Mesh Network

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In order to solve the limited energy and low throughput problems of the battery-powered wireless mesh network (WMN), an IEEE 802.11n based multi-radio multi-channel energy balancing and high throughput protocol (EBHT) for battery-powered emergency WMN is presented in this paper. EBHT optimizes the route path planning to achieve the energy balance by taking WMN nodes' residual energy, client accessed condition and route paths' link quality into account. It also assigns different high quality channels for adjacent nodes to improve the client communication performance and introduces dual-radio multi-channel allocation algorithm to increase network throughput. The EBHT's performance is evaluated by designing and implementing an IEEE 802.11n based WMN node. The results show that EBHT can improve WMN's throughput, enhance the communication reliability and optimize the node energy consumption. Compared with the traditional Mesh protocols, EBHT is more suitable for battery-powered emergency WMN.

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1.**Introduction**

Wireless Mesh Network (WMN) is a hot research topic in both academic and industry field. It's a self-organization, self-matching wireless network which is easily to be deployed. WMN consists of mesh clients and mesh routers, while the mesh routers form the wireless backbone and cooperate with the wired network to provide the wireless coverage for all mesh clients. WMN has been prevalently applied in industry monitoring, emergency services, smart city, and etc [1].

In most cases of emergency WMN, multi-hop wireless connection is widely used due to its extension of the communication distance. However, with the increasing quantity of wireless hops, the WMN's throughput will decrease accordingly. The throughput problem is primarily caused by the half-duplex and channel contention in the single radio nodes. Single radio nodes can't receive and transmit packets at the same time[2-4]. They must receive first and then transmit in order to finish a reply. Similarly, single channel wireless networks usually have low transmit rate due to the neighboring interference.

And, due to the higher demand for high-speed transmission, IEEE 802.11n standard has been adopted to deploy the emergency WMN. IEEE 802.11n has several special features of improvements for high throughput such as multiple input multiple output (MIMO), channel bonding and MAC layer frame aggragation. It can provide up to 600Mbps PHY transfer rate when using 4 data streams and 40MHz channel[5]. Whereas, IEEE 802.11n consumes more power than IEEE 802.11 a/b/g does. The power consumption is an important element for emergency WMN nodes, especially for the battery powered router nodes. If the battery runs out of power, the routers will stop working, and even the neighboring routers and clients' communications will be influenced too. Furthermore， IEEE 802.11n is more suitable for point-to-point communication than multi-hop communication, therefore, the multi-hop IEEE 802.11n comes to be a key point of WMN research.

In recent researches, many routing layer and MAC layer protocols were proposed to enhance the performance of IEEE 802.11n Mesh networks. Among these, IEEE has been working on IEEE 802.11s standard to improve the multi-hopping capacity. The IEEE 802.11s task group (TG) aims to standardize the WMN by defining the PHY and MAC layer protocols to support information transmissions under self-configureured mesh network topology[1, 6]. Figure.1 shows the mesh network topology where devices are connected with many redundant interconnections between network nodes. But, the newest standard has not been widely applied and spread.

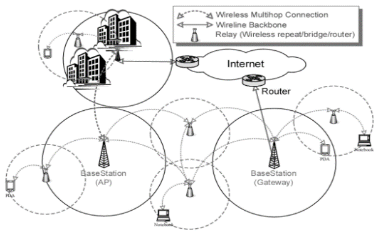

Figure.1: Mesh Network Topology

AN Le proposed a load-aware routing metric (LARM) for multi-radio wireless mesh networks. LARM can help find paths that are better in terms of balance load and reduction of the flow interference by capturing the differences in the transmission rates, packet loss ratio, intra / inter flow interference and traffic loading in the multi-radio WMN[7]. A. P. Subramanian formulated and addressed the channel assignment problem in multi-radio multi-channel WMN, and designed the centralized and distributed algorithms which assign channels to communication links in the network with the objective of minimizing network interference[8]. C. E. Perkins presented an on-demand distance vector routing protocol (AODV) which has already been adopted as Ad hoc networks RFc standard. The AODV avoids the counting-to-infinity problem of other distance-vector protocols by using sequence numbers on route updates.

With multiple radios, nodes can receive and transmit packets simultaneously. Some multi-radio WMN protocols equip the wireless nodes with more than one radio or wireless interface, and assign the radios with centralized, static, and dynamic channel schemes to improve WMN throughput and the capacity of resisting interference[3,10]. Nevertheless, these protocols hasn't considered the extra power consumption caused by the multiple radios.

Some multi-channel MAC layer protocols were proposed to improve the performance of the wireless networks[11-13]. These protocols can make good use of the channel resource, but fail to consider the real-time quality of the channel. If nodes switch to the channels which are in bad conditions (interference, over-loaded, etc.), the network's communication performance will be further decreased.

In this paper, we proposed an EBHT cross-layer protocol for battery-powered emergency WMN which can not only increase the mesh network's throughput by adopting multiple channels assignment algorithm and equipping the router nodes with multiple IEEE 802.11n radios, but also improve the energy efficiency and prolong the battery-powered WMN router nodes' lifetime by using high reliable low-power multi-hop routing paths selection algorithm. In addition, we have developed an IEEE 802.11n-based WMN testbed to evaluate the EBHT's performance.

2.Characteristics of the Emergency WMN

The Emergency WMNs are usually deployed in harsh areas or accident scenes to provide temporary emergency communications. The characteristics of this application are described as follows:

1) Due to lack of external power supplies in above-mentioned areas, most emergency WMN devices are powered by the self-contained batteries.
2) Multi-hop network is needed due to the network's irregular and varying topology.
3) High throughput is desired to transmit and relay the real-time videos, voices, etc.
4) The network's transmission must have high reliability and quality to guarantee the emergency QoS (quality of service).

3.EBHT Cross-Layer Protocol

In most WMN applications, multi-radio protocols can significantly improve the network's transmission performance. In theory, the simultaneous using of multiply radios over different channels can provide a liner throughput increasing to the most extent. But in the real world application, the more radios nodes are used, the higher energy consumption, hardware cost and data process will be caused. For most battery-powered emergency WMN router nodes, it is unsuitable to greedily pursue the high performance by equipping the nodes with large number of radios.

EBHT introduces a dual-radio assignment mechanism to reach the balance between the performance requirement and power consumption. With two IEEE 802.11n radios, router nodes can receive and transmit simultaneously, and full-duplex communication can be achieved. To make the best usage of the radios, EBHT makes following requirements:

1) R_A^I (Radio A of router node n_i) works at 5-5.8 GHz to form the backbone of the emergency WMN. The network is deployed in the harsh areas where the external wireless interference is very little. Therefore, we take no account of external interference during forming the backbone.
2) R_B^I (Radio B of router node n_i) works at 2.412-2.483 GHz to provide the mesh clients with wireless coverage.
3) All nodes' radios have the same receiving and transmitting capabilities.

Moreover, to meet the high data throughput, transmission reliability and energy efficiency requirements of the emergency WMN, EBHT combines the reliable-efficient multiply hop)routing path selection algorithm (REMH) with the dual-radio based multi-channel MAC protocol (DRMC). REMH takes link quality of transfer route, energy-efficiency and CPU loading into account during route selection to build more stable and reliable backbone networks. DRMC allots each neighbor WMN node best quality and non-overlapping channels to improve the utilization and increase networks' throughput and reliability.

3.1REMH Routing Path Selection Algorithm

REMH keeps on dynamically building the network between each active WMN node and the gateway node GW, and only the radios that work at 5-5.8 Ghz are involved in this process. Each WMN node sustains a neighbor node information table which is shown in Table 1.

Fields	Describes
IP address	Neighbor node's IP address
MAC address	MAC address of neighbor node' s 5Ghz radio
Channel	Channel used by neighbor node's 2.4Ghz radio
Accumulation packet received rate	Accumulation packet received rate between neighbor node and GW
energy-performance coefficient	Performance coefficient of route from neighbor node to GW
remaining energy rate	Neighbor node's current remaining energy percentage
Accessed client number	Current accessed client number of neighbor node

Table 1: Nerghbor Node Information

In order to strengthen the WMN's communication reliability, REMH uses packet received rate to evaluate the wireless link quality. In this evaluation system, link quality Q and packet received rate $P_{i,j}(CH_{index})$ are defined as follows:

$$Q_i = \prod_{k=i}^{GW} P_k = P_{i,j} \cdot Q_j \cdot \tag{3.1}$$

$$P_{i,j}(CH_{index}) = \frac{h_{i,j}}{\mu_i \times T} \cdot \tag{3.2}$$

Where n_j is the forwarding node of n_i, Q_i is the product of packet received rate of every forwarding nodes between n_i and GW, $P_{i,j}(CH_{index})$ refers to the rate of received packet $h_{i,j}$ from n_i to n_j within the time T on channel CH_{index}, while μ_i presents the packet sending speed of n_i.

To improve the energy efficiency, n_i will detect its residual power percentage E_i in real time and use it as an important factor to transmit the route selection. Considering in real-world application each node with different energy consumption speed, this paper assumes that CPU running consumption of each node is nearly the same.Thus the radio's transmitting and receiving data comes to be the major operation of energy consumption. The energy consumed by radio receiving and transmitting data can be calculated as follows[14]:

$$E_{Tx}(l,d) = E_{radio}(l) + E_{Tx-amp}(l,d) \cdot \tag{3.3}$$

$$E_{Rx}(l) = E_{radio}(l) = lE_{elec} \cdot \tag{3.4}$$

$$E_{Tx-amp}(l,d) = \begin{matrix} l\varepsilon_{fs}d^2, & d < d_0 \\ l\varepsilon_{mp}d^4, & d > d_0 \end{matrix} . \tag{3.5}$$

Where $E_{Tx}(l,d)$ and $E_{Rx}(l)$ denote the node's energy consumption of transmission and receiving l bit data over distance d, $E_{Tx}(l,d)$ is composed of wireless radio circuit's energy consumption E_{elex} and power amplification circuit's energy consumption $E_{Tx-amp}(l,d)$ of sending l-bit data. If d is smaller than threshold d_0, $E_{Tx-amp}(l,d)$ adopts the free space propagation model, otherwise, $E_{Tx-amp}(l,d)$ adopts the multipath attenuation propagation model.

According to (3.3), n_i's energy consumption R_i is directly proportional to l, that is to say, R_i will grow with the increasing of n_i's accessed client number N_i. And the CPU loading will also get increased which may cause bigger transmission delay when the WMN node connects to more clients. So, during the process of selecting the routing paths, REMH uses N as an important index to evaluate the energy consumption and CPU's load with

$$\zeta_{j,i} = Q_i \cdot E_j \cdot \frac{1}{(N_j+1)^{\alpha+1}} = P_{i,j} \cdot Q_j \cdot E_j \cdot \frac{1}{(N_j+1)^{\alpha+1}} \quad . \tag{3.6}$$

Where α denotes the CPU's load-delay parameter which can be adjusted according to CPU's processing ability and the WMN's real-time requirement. $\zeta_{j,i}$ is n_j's energy-performance coefficient of becoming to be n_i's forwarding node. The bigger $\zeta_{j,i}$ is, the longer survival time and better overall performance n_i's routing path through n_j will have.

The following steps give the details of REMH.

Step 1: GW periodically broadcasts a set of network test messages NT_MSG which consist of node information and time stamp.

Step 2: Each WMN node receives and forwards GW's NT_MSG, then calculates the packet receive rate based on NT_MSG.

Step 3: GW sends out the network configureuration message NC_MSG after finishing the network testing. Once receiving the NC_MSG, WMN node sends out the route matching message RM_MSG which consists of source node ID, source node residual power, source node accessed client number, source node accumulation packet received rate and wireless coverage channel to its neighbor node immediately.

Step 4: On receiving n_j's first NC_MSG, n_i will calculate $\zeta_{j,i}$ by (3.6) and select the node that has the largest ζ to be its forwarding node. Then, n_i will update its neighbor node information table, and send the routing require message RR_MSG to the selected node and NC_MSG to its neighbor nodes.

Besides, the newly joined node will broadcast network access request message, and select the just node with the largest ζ to be its forwarding node based on the NC_MSG responded by the neighbor nodes during current communication period. Within this communication period, the newly joined node will not affect other nodes' communication. When some nodes are out of the network during the period, the nodes that forward data to these dropped nodes before will re-select the forwarding node as the newly joined nodes.

3.2 DRMC MAC Protocol

DRMC mainly works during the WMN nodes' wireless coverage period. Each node dynamically maintains an available channel queue when the channel elements are ordered upon the local channel quality and neighbor nodes' channel usage condition. The local channel quality is evaluated as follows:

$$E_t(CH_{index}) = \beta E_{t-1}(CH_{index}) + (1-\beta)\,P_t(CH_{index}) \;, \quad \beta \quad (0,1) \cdot \tag{3.7}$$

Where $P_t(CH_{index})$ and $E_t(CH_{index})$ denote the packet received rate of the node in channel CH_{index} within the time slot and the channel CH_{index}'s quality estimation. β is the historical channel quality impact factor. The influence of the historical channel quality on the current quality estimation can be controlled by adjusting β. The larger the $E_t(CH_{index})$ is, the better the channel CH_{index} performance will be.

After forwarding the routing path selection is finished, each node gets its neighbor nodes' ID. During the coverage channel competition, each node identifies the sequence of choosing channel by comparing its node and neighboring nodes' ID. The larger the node's ID is, the higher priority the node has. And the node will choose the channel queue's first channel to be the coverage channel. Once finishing the channel selection, node will broadcast a channel-selected message CS_MSG immediately to inform its neighbor nodes of the channel selection result. Then, all nodes that have received CS_MSG will remove the neighbor node's coverage channel and the adjacent channels to the end of its local channel queue.

When the network topology changes, or the channel quality gets worse, node will reassign the coverage channel by DRMC to make full use of the high quality channel and try to avoid using the interferential channel for coverage of neighbor nodes.

4. Performance Evaluation

An IEEE 802.11n based Mesh node testbed was designed to evaluate the EBHT protocol's performance. This testbed is equipped with AR9350 and AR9592, which are both 2.4/5 GHz dual-band 2×2 IEEE 802.11n RFs. Besides, AR9350 is integrated with a 533MHz processor which is used to process the data and manage the communication protocol. Furthermore, to the faciliate the computer connection, an ethernet controller QCA8327 is mount to AR9350 through the RGM II interface. The hardware testbad is shown in Figure.2, and its structure is shown in Figure 3.

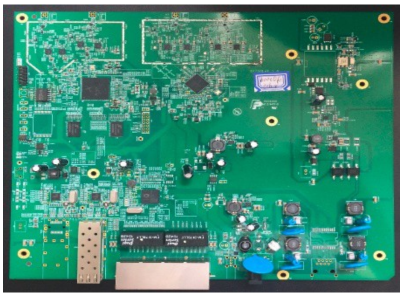

Figure 2: Testbed Hardware

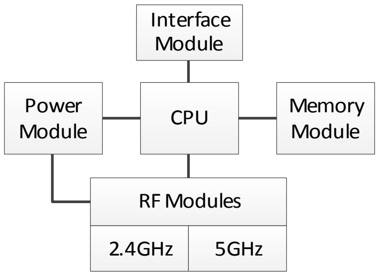

Figure 3: Testbed Hardware Structure

16 Mesh node testbeds and 4 interference sources were used to build the test Mesh network. Every Mesh node is equipped with a 12000 mAH Lithium-ion battery and a 11 dBi omni antenna. For each node, AR9350 worked at 2.4GHz frequency band to realize wireless access, while AR9592 worked at 5GHz frequency band to form the backbone of the WMN. The client was simulated by the computer with the NETGEAR WNA3100 Wi-Fi card, and the performance parameters were recorded by the NETIQ CHARIOT.

All nodes were equipped with full charge state batteries and deployed on the open-sided site to test the communication energy consumption and survival time of WMN nodes. Figure 4 shows the standard deviation of nodes' residual energy percentage at different periods of time under AODV and EBHT. Difference value of residual energy percentage among EBHT nodes was smaller than that of AODV nodes at every time period. Compared with AODV protocol, EBHT achieved a better energy-balanced performance. Figure.5 shows the survival node number in different time period under AODV and EBHT. EBHT nodes got longer lifetime due to the EBHT's energy-balanced character which can postpone the GW nearby nodes' death time by collecting the client accessed number and residual energy percentage during route planning. Moveover, it helps the WMN improve the communication stability and efficiency.

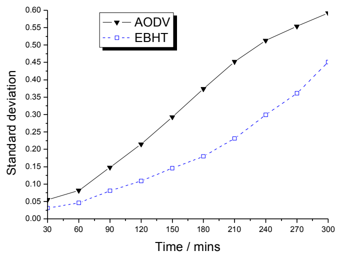

Figure 4: Standard Deviation of Energy Percentage

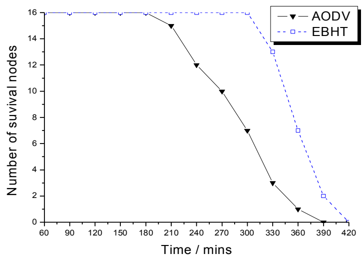

Figure 5: Survival Node Number

Figure 6 and Figure 7 present the network's average packet drop rate (PDR) of different number of UDP clients and during different periods of time respectively. When the number of the whole network's accessed client is small (less than 25), PDR of EBHT and AODV are nearly the same. When the number of accessed clients increases, it's apparent that EBHT gets lower PDR than AODV due to DRMC multi-channel allocate strategy. DRMC makes good use of the channel resource and reduces the internal co-channel conflict and the external wireless interference. Furthermore, PDR is an important factor for REMH to plan forwarding path. Therefore, EBHT can significantly improve the reliability of the WMN's communication.

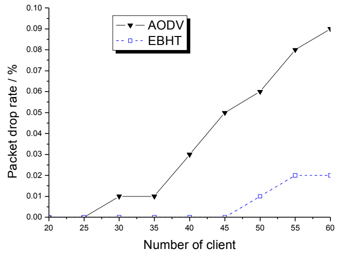

Figure 6:PDR under Different Number of Client

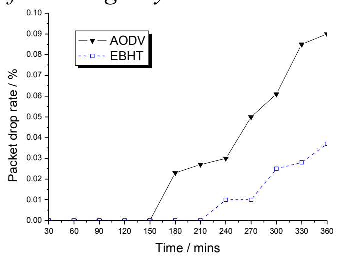

Figure 7: PDR under Different Time Period

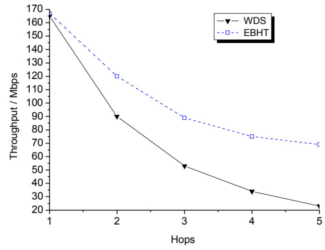

Figure 8: Network Throughput

Figure 8 shows the throughput comparison of single-RF Wireless Distribution System (WDS) and dual-RF EBHT under the chain backbone topology. Both the EBHT and WDS throughput drop when the node hops increases, which is mainly caused by radio collision. But EBHT throughput maintains at least 30 Mbps higher than WDS throughput from 2 hops to 6 hops with the use of dual-radio and multi-channel. EBHT's dual-radio technology can help reduce the radio collision and avoid the extra energy consumption, while EBHT's multi-channel technology and route planning algorithm can balance the channel loading and reduce the re-transmitting caused by packet loss. All in all, EBHT gets good performance in improving the throughput.

5. Conclusion

In this paper, we proposed an IEEE 802.11n based multi-radio multi-channel protocol EBHT for the battery-powered emergency WMN. The EBHT fuses the reliable and efficient route path selection algorithm REMH and dual-radio based multi-channel MAC protocol DRMC to meet the lifetime and throughput needs of battery-powered WMN systems. REMH adopts nodes' energy-performance coefficiency as an important route path selection criterion to prolong WMN lifetime and improve network's packet received rate, while DRMC avoids wireless interference and improves network's throughput by assigning a non-adjacent channel to its neighboring nodes. Besides, we designed and implemented the IEEE 802.11n based dual-radio WMN testbed to evaluate the EBHT's performance. The evaluation results show EBHT is suitable for battery-powered emergency WMN with its comprehensive efficient performance. It can improve WMN's throughput, enhance communication reliability and optimize node energy consumption.

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