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On energy-balanced resource scheduling policy optimality for QoS assurance in multi-hop wireless multimedia networks

Wireless Multi-hop Energy Balancing

Lin Xing · Wei Wang · Sunho Lim · Feifei Gao · Kun Hua

Abstract Energy balancing is an essential issue for scenarios of multi-hop wireless networks powered by batteries, for example, in disaster relief applications. In this paper, we propose a new transmission scheduling policy to extend the lifetime of a linear chain topology based multi-hop wireless multimedia network by maximizing the energy-balancing between routers. Two error-control techniques, Forward Error Correction and Automatic Repeat reQuest (ARQ), are adaptively deployed by the proposed strategy to achieve the maximal energy-balancing with the minimal quality requirement constraint. By considering the energy-balancing and the lower bound of multimedia quality constraint, the optimal channel coding redundancy and the optimal ARQ data retransmission strategy are applied to multimedia packets when those packets pass through each router in data transmission. To reduce the computing complexity, we simplify the solution by grouping multimedia packets with similar quality contribution, separating the global quality requirement into multiple local quality requirements, and allocating the optimal local quality requirement to each multimedia packet group. The simulation results show the proposed approach can significantly improve energy-balancing and lifetime of the multi-hop wireless multimedia network in both linear chain topology and more complex topologies.

Keywords Energy balancing · Multi-hop wireless networks · Channel coding

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1 Introduction

Recently, multi-hop wireless multimedia networks are gaining more attentions due to its low cost in expediently recovering communication services in many disaster (e.g., earthquake, tsunami, flooding, etc.) relief applications. In such applications, routers in the mobile and embedded wireless multimedia networks are usually powered by limited battery resource. Thus, how to prolong the multimedia service time using multi-hop wireless network with finite energy becomes a critical issue. This is especially true in the cases that it is hard or impossible to recharge or replace exhausted batteries. For example, after the disaster caused by tsunami and earthquake happened in Japan in 2011, the infrastructure of wired communication networks and power supply systems were destroyed completely in lots of areas. In order to provide communication support, a battery-powered multi-hop wireless multimedia network could be built temporarily. In this case, how to prolong the communication service should be paid more attention in addition to satisfying Quality of Service (QoS) and latency requirement. In this paper, the

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network lifetime is defined as the duration before the first router exhausts its energy [1]. Because once a router runs out of its battery energy and the router is in a crucial position of the network, it may cut one or more communication paths and badly affect the performance of network service. However, it is impossible to avoid energy consumption discrepancy between routers naturally, because routers at different positions have different workloads, which results in various energy consumptions. Obviously, the lifetime of the wireless networks will be reduced if one node always consumes more energy than other nodes, even though other routers still have much residual energy. More attention should be paid for how to maximize energy-balancing, which can prolong the lifetime of wireless networks powered by limited energy.

Further more, the multimedia communication has a special property that different packets in a multimedia stream may have different importance levels in light of the contribution to multimedia quality received in the destination. So the quality contribution and the energy consumption of each multimedia packet should be jointly considered for improving the network energy-balancing and providing the minimum QoS requirement.

Various cross-layer optimization designs for multimedia applications based on multi-hop wireless networks have been investigated by recent research. However, most of them focused on maximizing multimedia QoS, but seldom considered the energy-balancing of wireless networks. In research [2], the authors surveyed scheduling techniques and reviewed desirable features and classifications for wireless multi-hop networks. Several scheduling algorithms such as TDMA, CDMA, and multi-hop packet networks are discussed. In research [3], a collaborative algorithm is proposed for maximizing the performance of multimedia service over multi-hop wireless enterprise mesh networks by collaborating available resource among participating peers. In addition, scalable coding and cross-layer strategies were deployed to enhance the efficiency of resource exchanges under various channel conditions. In research [4], the authors discussed the application of multiple antennas in multi-hop wireless networks for supporting multimedia applications. In research [5], the authors designed a cross-layer strategy to perform optimal routing of multiple description multimedia video in multi-hop wireless networks. A branch-and-bound framework and Reformulation Linearization Technique (RLT) were developed and exploited to find the optimal solution. A similar technique was used in research [6] to solve the optimal path selection and rate allocation problem for multimedia sessions in wireless mesh network. In research [7], a cross-layer algorithm was proposed for maximizing video QoS in multi-hop wireless mesh networks with latency requirement. Various control parameters that across protocol layers and across various nodes were considered and optimized. An overlay network was assumed to supply necessary information for optimization. In research [8], the authors optimized cross-layer parameters at physical layer, Medium Access Control (MAC) layer, and application layer for maximizing video streaming quality over noisy wireless multi-hop networks. In addition, optimal deployment of path diversity was also studied to solve the link error problem. In research [9], to improve multimedia distortion and fairness in multi-channel, multi-radio, and multi-hop wireless networks, the authors developed a general distortion model, formulated the question and provided a fully distributed scheduling. In research [10], an overlay infrastructure was deployed to feedback necessary network conditions with various network horizons for various cross-layer strategies adaptation. In research [11,12], the authors proposed a distributed cross layer algorithm to weight the priority of video packets in simultaneous real-time video streaming sessions. To maximize the decoded video quality, the video packets with higher priority were guaranteed with lower queuing delay and transmitted over the most reliable link in multi-hop wireless networks. An optimal distributed scheduling which joint optimization of multiple description, optimal rate control, and routing scheme was investigated in [13,14] for video streams in multi-hop wireless network with resource limitation. A distributed rate control and routing algorithm and a simplified version of solution were proposed for dynamic wireless network conditions with various video packets. A joint forensics-scheduling was proposed in [15] for improving delay-sensitive multimedia application and in [16], the authors studied how the constrained network information impacts transmission scheduling. Various cross-layer optimizations for achieving the best multimedia performance over multi-hop wireless networks were proposed in [17–23], in which new strategies about MAC, routing, energy distribution, and rate allocation were discussed and proposed. However, the above research focused on maximizing the end-to-end multimedia quality, with little consideration of energy constraint, which is an important factor for the wireless multimedia networks with limited energy resource.

Fundamentally different from the above research, we propose a new optimization scheduling policy of improving energy-balancing of each communication path to extended lifetime of battery-powered multi-hop wireless multimedia networks. In our preliminary research [24] which has been published as the conference version of this paper, we have proposed an adaptive channel coding assignment approach to optimize energy-balancing along a single communication path. In this paper we fundamentally improve the preliminary design, provide a more comprehensive solution, and integrate network retransmissions into the optimization framework. Different from our preliminary work, the new proposed scheduling policy integrates two strategies: (1) For the routers with higher energy level, allocating more channel coding redundancies and applying more data retransmissions

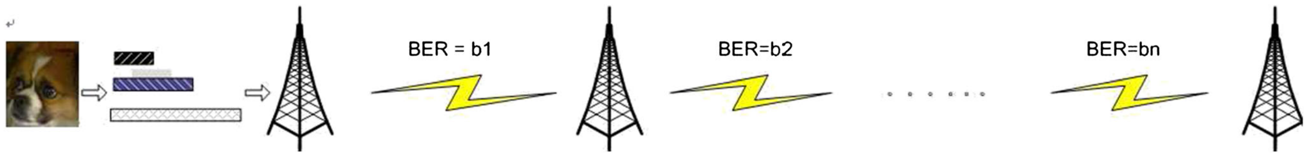

Fig. 1 Linear chain multi-hop wireless multimedia networks topology discussed in the paper

for improving data delivery quality with more energy consumption. (2) For the multimedia packets with more quality contributions, adding more channel coding redundancies and applying more data retransmissions for improving the reliability of end-to-end multimedia transmission. Channel conditions and size of multimedia packets are also considered for the tradeoff between energy-balancing and multimedia quality.

The rest of the paper is organized as follows. In Sect. 2, we present the scenario of battery-powered multi-hop wireless multimedia networks, and mathematically formulate the energy-balancing problem with QoS constraint. In Sects. 3, 4, and 5, we present the proposed optimal quality-assured energy-balancing scheduling policy. Several cross-layer parameters are estimated for optimizing channel coding allocation and data retransmission. In Sect. 6, we simplify the solution to reduce the computation overhead. In Sect. 7, simulation results are shown and discussed. In Sect. 8, we conclude the paper.

2 Problem formulation

In this paper, we do not discuss routing and data distribution strategy in details, which also could influence the energy-balancing of wireless networks. We focus on the resource allocation along a single path after ad-hoc routing protocols select a certain communication path between any pair of the source node and the sink node. The proposed policy optimizes the energy-balancing of the selected communication path, which is represented as a linear chain topology of multi-hop wireless multimedia networks, as the Fig. 1 shows. The proposed strategy can be widely applied for enhancing the lifetime of any multi-hop wireless networks powered by limited energy. A better performance would be achieved if cooperated with routing protocols that considering the energy-balancing of the networks. The lifetime of wireless networks can be prolonged by the proposed strategy, even though the strategy just focuses on a single communication path, because extended lifetime of each communication path would result in a longer service performance of whole networks.

As Fig. 1 shows, a multimedia file contains a number of packets with various sizes and quality contributions. These packets are sent from the source node to the sink node through a few routers, which are selected by the ad-hoc routing protocols. The forwarding routers along the path have different energy consumptions and residual energies. Our purpose is to optimize the energy-balancing and satisfy the minimal end-to-end quality requirement after transmitting the multimedia file. To achieve this purpose, the optimal channel coding redundancy or and the optimal data retransmission is applied on each hop in the process of data transmission. An overlay feedback network infrastructure [7] is used to collect the information about residual energy on each router and channel condition on each link, with ultra-low duty cycle, in a way similar to [24]. The channel condition can also be estimated by the method proposed in [25]. About quality constraint, we choose the multimedia distortion, which is widely used for multimedia quality modeling. The distortion reduction of each multimedia packet can be either measured or estimated. In terms of measurement it is done by calculating the decoded image quality improvement in a way similar to existing research [26]; in terms of estimation it is done according to the wavelet coefficient square error units [27]. In this paper we follow the estimation approach, where the distortion reduction of each packet can be directly acquired from the JPEG2000 codec. More constraint conditions such as delay can also be applied seamlessly to the proposed policy, as long as the restriction is influenced by the error-control techniques deployed in the paper. Table 1 summarized the symbols and notations used in the equations in this paper.

If a router in the linear chain communication path runs out of energy, the transmission path will be cut off and lose the communication functions. To extend the communication service and to make full use of limited energy, we provide a new strategy to improve the energy-balancing of the network. The energy-balancing is defined as the difference between two nodes with the highest and the lowest residue energy respectively in a ways similar to [28], and we follow the symbol definition in [29]. The energy-balancing optimization is formulated as:

$$[G] = \arg\min \left\{ \max_{\forall i \in S} (e_i) - \min_{\forall j \in S} (e_j) \right\} \tag{1}$$

subject to the QoS lower bound constraint:

$$E[D] \geq D_{\min} \tag{2}$$

where $[G]$ denotes the optimal resource allocation strategy (i.e., the channel coding rate or the optimal data

Table 1 Summary of the key notations used in the equations

Symbol	Notation
$[G]$	The optimal channel coding rate or data retransmission strategy
S	Set of all routers in the network
e_i	Residue energy of node i
$\max(e_i)$	The "highest energy" router
$\min(e_j)$	The "lowest energy" router
g	Channel coding rate or data retransmission
N	Total packet need to be transmitted
H	Total number of hops
$E[Q]$	Expected QoS
$D_{\min}$	Minimal quality requirement
d_i	End-received quality contribution of multimedia packet i
C	Total packet pass through the network
P	Packet path-pass probability
p_α	Packet link-loss probability on hop α
M	Length of original multimedia packet
a	Bits of channel coding redundancy
b	Bit error probability
e_{co}	Energy consumption of a certain router after receiving and transmitting data
P_t	Transmission power
P_r	Receiving power
l	Length of multimedia packet
r	Data transmission rate
t_o	Protocol overhead
D_{loc}	The optimal local QoS allocated to a certain packet group
$E[D]_{group}$	The expected end-received quality contributed by a certain packet group
$D_{re\_\min}$	The residue global QoS

re-transmission strategy) assigned to multimedia packets when they pass through different routers. These value lead to the minimal energy-difference and satisfy the lower bound of quality requirement. S is the set of all routers, e_i and e_j is the residual energy on router i and router j, respectively. $\max(e_i)$ and $\min(e_j)$ are the highest and the lowest residue energy of the routers, respectively. $E[D]$ denotes the expected end-to-end multimedia quality after data transmission. $D_{\min}$ denotes the minimum QoS requirement. Integrating Eqs. 1 and 2, the optimization transmission scheduling proposed in this paper achieves the optimal channel coding rate and the data re-transmission strategy for achieving both the maximal energy-balancing and the minimal quality requirement.

3 Modeling end-to-end multimedia quality

To improve traditional approaches which aim to achieve the maximal end-to-end quality but seldom considering the energy-balancing, we propose a new transmission scheduling framework which is composed of two optimal methods to improve the energy-balancing, and consequently extend the lifetime of wireless multimedia networks. In each hop of the liner transmission chain, the optimal channel coding rate or the optimal data retransmission strategies are applied to multimedia packets for achieving both energy-balancing and quality assurance. The information about Bit Error Rate (BER) and residual energy is collected to obtain the optimal transmission scheduling.

The expected end-to-end multimedia quality is estimated by considering the packet quality contribution and the related path-pass probability. Assume that there are N multimedia packets to be transmitted from the source node to the destination through H hops, i.e.: $\{h_1, h_2, \ldots, h_H\}$, and the related quality contribution of each packet is $\{d_1, d_2, \ldots, d_N\}$. After sending all multimedia packets, the final expected end-to-end multimedia quality can be expressed as the quality contribution summation of all packets weighted with related packet path-pass probability as follows:

$$E[D] = \sum_{i=1}^{C} (d_i \times P_i) \tag{3}$$

where C denotes the number of multimedia packets expected to be received on the destination. d_i is the expected quality contribution of packet i if received by the user with error free. P_i denotes the packet path-pass probability, which means the probability of packet i to be received by the user successfully. The multimedia packets may have the dependency among them, however, modeling of the total expected distortion reduction considering the dependency can be seamlessly integrated into the proposed approach. The Eq. (3) is generic, which presents both non-dependent and dependent multimedia packets distortion reduction expectation. When dependency is considered, the cumulative packet pass rate can be easily adjusted by including the factor of ancestor packet pass rate. This is because when ancestor packets are lost, the current packet is useless in decoding even if it is received correctly. Thus the proposed approach can seamlessly accommodate multimedia streams with or without packet dependency.

4 End-to-end quality analysis

Forward Error Coding (FEC) with spatial redundancy and ARQ data retransmission with temporal redundancy are two common error-control techniques for improving packet pass probability in noisy communication channels. Due to the redundancy information of FEC, more bandwidth is consumed and the throughput of networks is reduced. Compared with FEC, data retransmission technique requires lower system complexity, less processing overhead and less digital hardware support. The proposed scheduling strategy considers the channel condition and residual energy of each router to achieve the optimal resource allocation, which can avoid the above shortcomings by two steps: (1) allocating the optimal channel coding rate and data retransmission for reducing bandwidth consumption; (2) estimating the optimal data retransmission, and performing packets transmission.

The packet path-pass probability is required for estimating the end-to-end multimedia quality, which can be expressed as a consecutive multiplication of link-pass probability as follows:

$$P = \prod_{\alpha=1}^{H} (1 - p_\alpha) \tag{4}$$

where p_α denotes the link-loss probability of multimedia packets when they pass from router α to router $\alpha+1$. The link-loss probability influenced by two error-control techniques is analyzed respectively in the next two subsections.

4.1 Channel coding rate assignment

The packet loss probability can be significantly improved by applying FEC on multimedia streaming. Redundancy information enables receiver to detect and recover limited bit-errors. In general, more channel coding redundancy added to the original packet cause more recovery capacity and more data transmission reliability. The effect of FEC on packet link-loss probability under various parameters such as packet size, coding redundancy, and BER is estimated as follows [30].

$$p = \sum_{i=M+1}^{M+a} \binom{M+a}{i} b^i (1-b)^{M+a-i} \tag{5}$$

where p denotes the packet link loss probability, M denotes the size of original packet, a is the size of coding redundancy, and b is BER. The equation is the summation of all loss cases possibility that regarded as too many bit-errors to be corrected, weighted with related bit pass and bit loss probabilities.

4.2 Data retransmission assignment

To ensure the expected end-to-end QoS, multimedia packets need to be multi-transmitted in noisy channel condition. The packet link-loss probability after retransmission can be described as the probability of all retransmitted packets failing to pass the link. We express it as follows:

$$p = \left(1 - (1-b)^M\right)^r \tag{6}$$

Where r denotes how many times a multimedia data packet is retransmitted. $(1-b)^M$ denotes the probability of all M bits of a packet pass through an error-free link.

5 End-to-end energy balancing analysis

In the proposed approach, we optimize channel coding rate and packet retransmission for achieving maximal energy-balancing obeying the minimal quality requirement. Due to various importance levels of multimedia packets and versatile residue energy of each router, we deal with each packet on each hop in specific transmission scheduling scheme to get the optimal overall system objective. The transmission scheduling matrix is shown as follows:

$$[G] = \begin{bmatrix} g_{11}, g_{12}, \ldots, g_{1H} \\ g_{21}, g_{22}, \ldots, g_{2H} \\ \ldots\ldots \\ g_{C1}, g_{C2}, \ldots, g_{CH} \end{bmatrix} \tag{7}$$

where g denotes the channel coding rate or data retransmission times, and g_{CH} is the scheduling scheme for multimedia packet C on hop H. To achieve the optimal data transmission scheduling policy that leads to maximal energy-balancing, energy-consumption and residual energy on each node should be accurately estimated. The energy consumption on each node after transmitting C multimedia packets is expressed as:

$$e_{co} = \sum_{i=1}^{C} \left(\frac{P_r \times (l_i \times g_{i\_in}) + P_t \times (l_i \times g_{i\_out})}{r} + t_o \right) \tag{8}$$

where e_{co} denotes the energy consumption after data transmission, P_r and P_t denotes the transmission power and receiving power respectively. l_i is the size of original multimedia packet i, g_{i_in} and g_{i_out} is the channel coding rate or data retransmission allocated to the packet i on the previous hop and the next hop respectively, r denotes the transmission data rate and t_o is protocol overhead. The residue energy e of a certain router could be calculated as follows where := denotes an updating operation:

$$e := e - e_{co} \tag{9}$$

The energy-balancing of network is optimized by deploying the optimal data transmission scheduling. The design guideline of the proposed strategy can be described as: First, evaluate the residual energy on each node and estimate end-to-end service quality with different channel coding allocations or data retransmission strategies. Second, find out the optimal scheduling scheme that results in the maximal energy-balancing between two nodes with the highest and the lowest energy level within the lower bound of quality requirement.

6 Design simplification

Above analysis provides the complete solution to get the optimal energy-balancing of the network, however, the computing overhead of the globally optimal solution is too high to be practical. For example, assuming that there are N packets needed to be transmitted, L hops along the path, and the channel coding rate choice and data retransmission choice is 4, then the complexity of achieving the globally optimal solution is 4^{L*N}. We simplify the optimal scheduling with 3 steps: (1) Group multimedia packets according to the multimedia contribution and then all packets in the same group apply the same transmission scheduling scheme. (2) Separate the global minimal QoS requirement $D_{\min}$ to multiple local minimal QoS requirements D_{loc}, and assign them to each packet group. We propose an algorithm called Quality-Allocation Scheduling (QAS) to specify the optimal local minimal QoS D_{loc} to each packet group, which is illustrated in Algorithm 1. (3) Obtain the optimal scheduling strategies for each packet group by jointly considering the energy-difference and the related D_{loc}.

The QAS algorithm first prioritizes each packet group such that "more important" groups have higher priorities, and then separates the global $D_{\min}$ to multiple local D_{loc}. The optimal D_{loc} for each packet group is achieved base on the strategy that more resource is allocated to the packet group with higher priority. The optimal local minimal QoS D_{loc} for each packet group is expressed as:

$$D_{loc} = \begin{cases} E[D]_{group} & E[D]_{group} \prec D_{re\_\min} \\ D_{re\_\min} & E[D]_{group} \geq D_{re\_\min} \end{cases} \tag{10}$$

where D_{loc} denotes the optimal local QoS allocated to a certain packet group, and $E[D]_{group}$ denotes the expected end-received quality contributed by a certain packet group if all multimedia packets in the group are received correctly. $D_{re\_\min}$ denotes the residue global QoS, which is equal to $D_{\min}$ before local QoS allocation, which can be calculated as:

$$D_{re\_\min} := D_{re\_\min} - D_{loc} \tag{11}$$

Algorithm 1 : Quality-Allocation Scheduling.

Step1. Prioritize each packet group.
Step2. Allocate D_{loc} to each group in a priority-descending order.

1. Calculate D_{loc} of current group according to equation (10).
2. Calculate $D_{re\_\min}$ according to equation (11).
3. Go to Step2.1 to calculate the optimal D_{loc} of next packet group with less priority until done.

For example, there are three packets $d_1 = 80$, $d_2 = 50$, $d_3 = 150$ waiting for transmission, and $D_{\min} = 180$. According to the QAS algorithm the priority-descending order is $\{d_3, d_1, d_2\}$, and in the beginning $D_{re\_\min} = D_{\min}$. For d_3, since $d_3 \prec D_{re\_\min}$, then $D_{loc} = d_3 = 150$, the minimal QoS requirement for d_3 is 150, and $D_{re\_\min} = D_{re\_\min} - D_{loc} = 30$. For d_1, since $d_1 \succ D_{re\_\min}$, then $D_{loc} = D_{re\_\min} = 30$, the minimal QoS requirement for d_1 is 30, and $D_{re\_\min} = D_{re\_\min} - D_{loc} = 0$. In the same way, we get the minimal QoS requirement for d_2 is 0. Then, we apply the optimal coding rate strategy to transmit each packet group to achieve the optimal energy-balancing while meeting the related local QoS requirement.

As we see, the proposed simplified strategy illustrated in Algorithm 2 separates a complex global optimization problem into several local optimization problems. The globally optimal energy-balancing of the network after transmitting all multimedia packets can be approached by optimizing the energy-difference between routers after transmitting each multimedia packet group. The flow chart of the Algorithm 2 is illustrated in Fig. 2. After initialization, the multimedia packets will be grouped together based on distortion reduction contribution, and packets with higher distortion reduction contribution will be assigned with higher priority. Group resource allocation will be performed in an optimal fashion

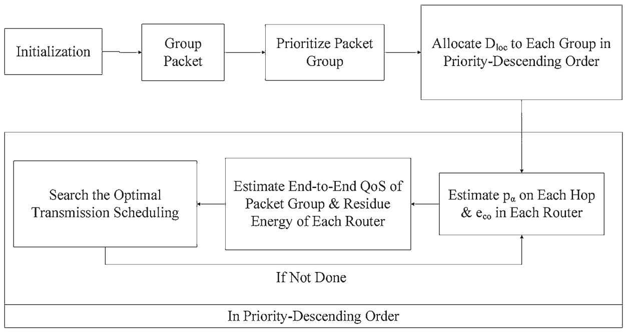

Fig. 2 Flow chart of the Algorithm 2

to guarantee the packets with higher priority will be served with more communication resource.

Algorithm 2 : Quality-Assured Energy-Balancing Scheduling.

Step1. Initialization. Define system configuration parameters: minimal quality requirement $D_{\min}$, transmission power and receiving power P_t and P_r, data transmission and receiving rate R, the bit link-loss probability b of each link, the protocol overhead t_o, the length of original multimedia packet l and the end-received quality d of each multimedia packet, the total packet number N, the number of total hop H along the transmission path, and the residue energy e for each router.

Step2. Group multimedia packets with the same importance level.

Step3. Allocate the optimal local minimal quality requirement D_{loc} for each packet group according to Algorithm 1.

Step4. Start from the packet group with the highest priority, in priority-descending order to allocate the optimal channel coding rate or data retransmission to each packet group with the corresponding minimal local QoS D_{loc}. All packets in the same group apply the same strategy.

1. Estimate the packet link-loss probability p_α on each hop with related b according to equations (5) (6) and estimate the energy consumption e_{co} in each router for transmission and receiving all packets in the group according to equations (7) and (8).
2. Estimate the final end-to-end QoS $E[Q]$ for the packet group according to equations (3) (4) and calculate the residue energy e of each router according to equation (9).
3. Search the optimal channel coding rate and data retransmission allocation causing the minimal energy-difference while meeting the related minimal local quality requirement D_{loc} according to equations (1) (2).
4. Go to Step4.1 to achieve the optimal strategy for the next packet group until done

7 Performance evaluation

In this section, we conduct the simulation study to evaluate the performance of the proposed quality-assured energy balancing scheduling in multi-hop wireless multimedia networks. The performance simulation is conducted with four aspects: (1) energy-balancing capability of the proposed approach within a single communication path; (2) whether improved energy-balancing lead to a longer lifetime of a path; (3) if the proposed approach guarantees the minimal quality requirement; (4) the performance of the proposed approach under different data distribution strategies in a complex network topology, which has multiple communication paths. A traditional approach that always allocates the maximal channel coding redundancy is deployed for comparison, and we just evaluate the energy-difference among forwarding routers.

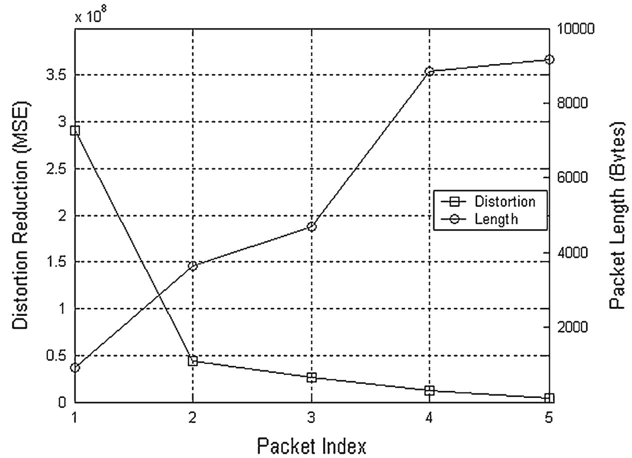

Fig. 3 Packet distortion reduction and the corresponding packet size of five packet types

In our simulation, we set parameters as follows: The network model has one source node, one sink node, and six forwarding routers. A multimedia file includes five types of multimedia packets, and each packet has different length and different quality contribution. Figure 3 illustrates the size and the related distortion reduction of each packet type. Transmission and receiving power is 20mW and 15mW respectively. The packet header of each multimedia packet is 6 bytes. The energy-difference is represented as a percentage of fully charged battery. Four preselected channel coding rates are 9/9, 10/9, 13/9, and 15/9. Four preselected retransmission strategies are 0,1,2,3. Five preselected transmission rate difference is 5, 10, 15, 20 and 25 %, which are represented as a percent of the first receiving rate that defaulted as 10Mbps. 5 % means the sending rate is 5 % higher than the receiving rate on each router, and the receiving rate on each hop is the same as the sending rate on the last hop. For example, 1st router's rate (10:10.5) => 2nd router's rate (10.5:11) => 3rd router's rate (11:11.5). To reduce the impact of channel condition on energy-balancing, the performance simulation was conducted under the same channel condition that BER is 1/100000. If not explicit specified, the default transmission

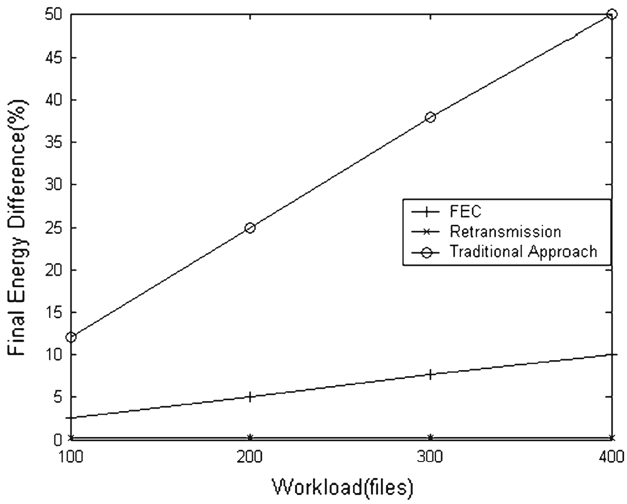

Fig. 4 Maximum energy discrepancy with various workloads

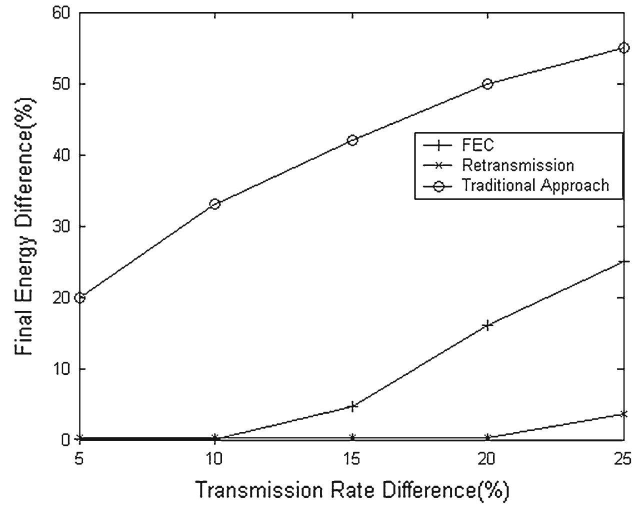

Fig. 5 Maximum energy discrepancy with various transmission rate differences

rate difference is 20 % and the default QoS constraint is 95 % file-pass probability.

Figure 4 illustrates the energy-balancing capacity of each strategy under different workloads. The workload is an amount of multimedia file transmitted over the network. The initial energy in each router is full, but the energy consumption is different in light of various transmission rates in different nodes, and energy-balancing decreases with bigger workload for the sake of transmission energy consumptions. Compared with traditional approach which always applies the maximal channel coding rate to maximize the end-to-end multimedia service quality, the proposed FEC and ARQ scheduling approaches significantly improved the energy-balancing of a single communication path. This is because the traditional approach does not consider the energy-balancing of the networks, but the proposed scheduling considers the energy-difference and the minimal quality requirement for applying the optimal channel coding redundancy and the optimal retransmission strategy on each hop when different types of multimedia packets pass through. Thus the energy-difference between routers is reduced and service quality is guaranteed. Data retransmission strategy achieves a higher energy-balancing than channel coding allocation, since the method provides a wider range of energy consumption difference.

Figure 5 illustrates the energy-balancing capacity of each strategy under different transmission rate differences. Bigger transmission rate difference increased consumption difference and energy-difference. As the Fig. 5 shows, with increased transmission rate difference, the performances of two proposed scheduling are significantly better than the traditional approach. Since the traditional approach has no ability to improve the energy-balancing, but two proposed approaches well distribute energy for each router and achieve

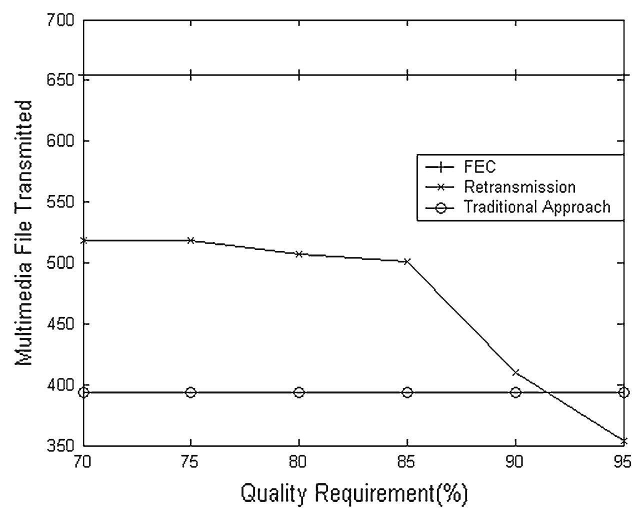

Fig. 6 The amount of passed file with various quality requirements

a better energy-balancing of networks. If the transmission rate difference is 15 %, the corresponding maximum receiving rate difference is 75 % (the minimum receiving rate is 10Mbps and the maximum receiving rate is 17.5Mbps), which is a large energy-difference. However, both of the proposed FEC and ARQ scheduling policies almost balanced the energy and obtained well energy-balancing performance.

Figure 6 illustrates the amount of multimedia files transmitted during the lifetime of network with different transmission scheduling strategies and various quality requirements. The result demonstrated the lifetime of networks with limited energy can be extended by improving the energy-balancing between routers. Both of error-control techniques achieved improved results with proposed strategy, especially for FEC, which transmits 50 % more multimedia files than the traditional approach. Data retransmission technique does

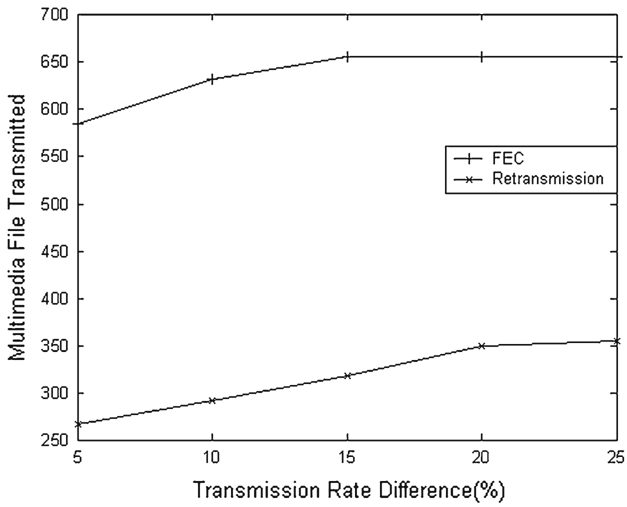

Fig. 7 The amount of passed file with various transmission rate differences

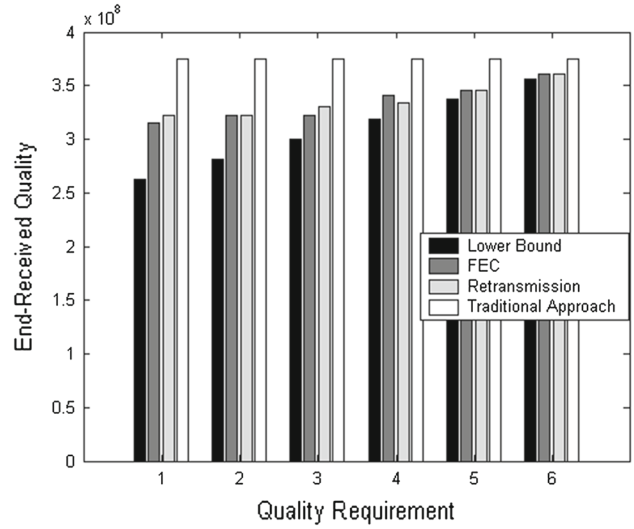

Fig. 8 End-to-end quality received for various quality requirements

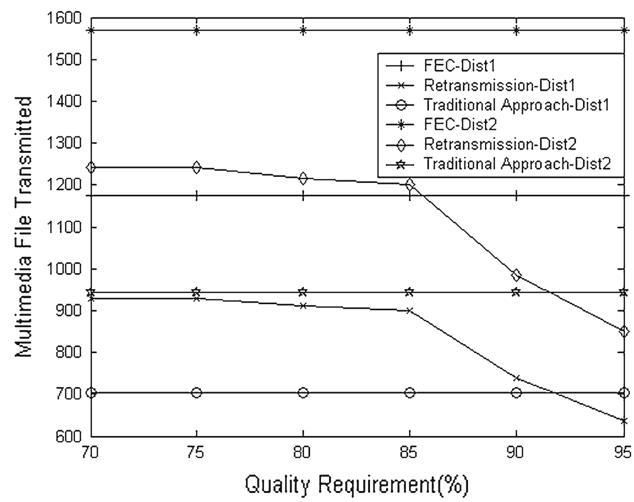

Fig. 9 The amount of passed file with various data distribution strategies and quality requirements in a multi-hop multi-path wireless mesh network

not obtain performance as good as FEC, but is still better than the traditional approach in most of cases. Since the method of data retransmission has less hardware cost than FEC, it is a good alternative in simple network systems with less hardware support. FEC provides a stable workload with various quality requirements for two reasons: (1) under different QoS requirements, the actual service quality does not change a lot (as Fig. 8 shows), (2) FEC is a high-performance error-control technique, which uses less channel coding redundancy to achieve significantly quality improvement. So improved quality does not take a lot of coding redundancy, and thus it costs less energy consumption. However, data retransmission is not as efficient as FEC in error recovery, so more energy is consumed for obtaining a higher service quality.

Figure 7 illustrates the final amount of transmitted multimedia files influenced by energy-difference. According to the lifetime definition of networks, the lifetime depends on the router with the lowest energy. If the quality constraint is satisfied, minimal coding redundancy or retransmission will be applied to the lowest energy router. However, if the energy-difference is already balanced, various channel coding redundancy or retransmission rather than the minimal one are applied to the lowest energy router to keep the energy-balancing and the service quality is improved. So the amount of transmitted multimedia files does not change if energy-difference is too large to be balanced, and the amount is reduced if the network is well balanced.

Figure 8 shows the end-to-end quality achieved by different strategies with different quality requirements. To make contribution to the final multimedia streams, the multimedia packet must be received error-free at the destination. Channel coding redundancy or data retransmission is applied to increase data pass probability. The traditional approach always applies the maximum channel coding rate to each hop, so a higher and more stable end-to-end quality is achieved. The proposed approaches consider the minimum quality requirement and the energy-balancing of the network. The optimal channel coding rate or data retransmission is applied to trade extra quality gain for precious energy-balancing. As this figure shows, the proposed approaches adaptively control the received quality which is always higher than the lower bound of quality requirement. The energy-balancing and the lifetime of networks are improved at the cost of acceptable quality reduction.

Figure 9 illustrates the lifetime extension of different scheduling strategies in a multi-hop multi-path wireless mesh networks topology [28], which is illustrated in the Fig. 10. The source node transmits media stream to the sink node via

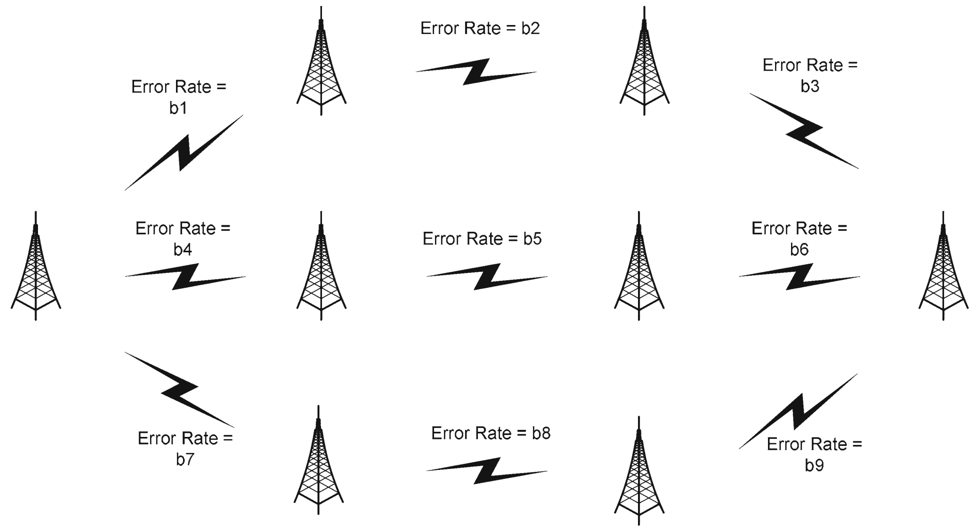

Fig. 10 Multi-hop multi-path wireless mesh networks topology

three communication paths, and each path includes six forwarding nodes. The initial power of all nodes in three paths is 100, 80 and 60 % of a full battery respectively. Two data distribution strategies are deployed: one strategy distributes the same traffic load to each path; the other considers the energy-difference between paths and allocates proper traffic to each path. The result shows the proposed energy-balancing strategy for a single communication path achieved improved performance in complex network topology. The lifetime of complex network topology is extended by prolonging the lifetime of each communication path. The data distribution strategy which is energy-balancing sensitive has a better performance, since it allocates more multimedia packets to the paths with higher energy level, and allocates less packets to lower energy path. The proposed approach can extend lifetime of networks with applications of routing protocols and data distribution strategy. In fact, the routing strategy considering energy-balancing is a another good alternative. In this paper we focuses on achieving energy balancing among the routers in one path.

Figure 11 illustrates the energy-balancing capacity of each strategy under dynamic channel condition. The BER is allocated randomly from 1/100000 to 1/10000. As the figure shows, the proposed simplified strategies very close to the optimal strategies, which try to achieve the global optimal solution and have higher computing overhead. Under dynamic channel condition and different transmission rate difference, the proposed strategies proved to be better than the traditional approach.

8 Conclusion

In this paper, we have proposed a novel transmission scheduling policy with cross-layer optimization to extend lifetime of multi-hop wireless networks with linear chain topology.

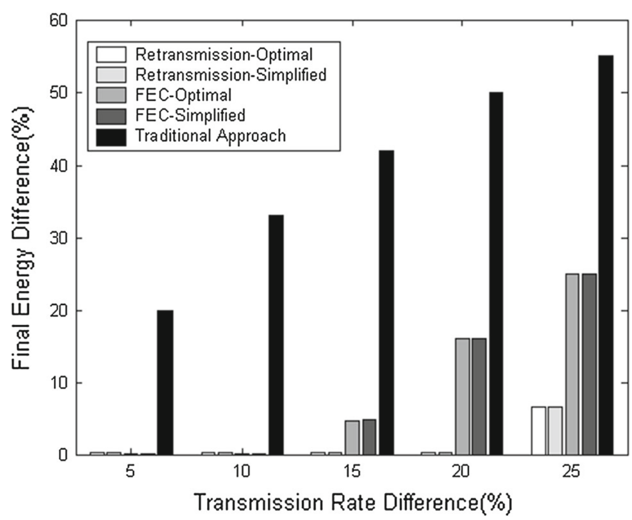

Fig. 11 Maximum energy discrepancy with various transmission rate differences. (The channel condition is allocated dynamically that BER is 1/100000- 1/10000)

The proposed transmission scheduling policy utilizes two error-control techniques to prolong the lifetime of network by keeping the energy-balancing while satisfying the quality constraint. The optimal channel coding rate and data retransmission strategy are performed on multimedia packets in the process of data transmission. Simulation results have shown the proposed scheduling strategy significantly improved energy-balancing and the lifetime of a linear communication path at the cost of acceptable quality reduction. The strategy also achieved improved performance in a simple multi-path networks topology with different workloads.

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