Ad Hoc Networks 19 (2014) 132–141

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Comparison of QoS-aware single-path vs. multi-path routing protocols for image transmission in wireless multimedia sensor networks

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form 24 February 2014
Accepted 26 February 2014
Available online 12 March 2014

Keywords:
Wireless multimedia sensor networks
Image transmission
QoS-aware routing protocols
Single-path routing
Multi-path routing

ABSTRACT

Wireless multimedia sensor network (WMSN) applications require strong multimedia communication competence. Therefore, in WMSN applications, it is necessary to use specific mechanisms in order to handle multimedia communication challenges and address desired energy efficiency and reliability goals. Nevertheless, the existing communication protocols are not suitable for the communication challenges and the desired goals. In this respect, specific mechanisms for prioritization, link-quality estimation and multi-path selection can be employed by quality of service (QoS)-aware routing protocols to meet the reliability and delay requirements of WMSN applications.

In this study a novel approach is proposed to set different reliability values for image packets for image transmission in WMSNs. Using this prioritization, important parts of an image are assigned high priority and take priority during data transmission. In order to evaluate the proposed approach, the performance of single-path and multi-path QoS-aware routing protocols has been investigated for WMSN-based image transmission applications. Specifically, comparative performance analysis of single-path routing and multi-path routing in image transmission have been conducted in terms of peak signal-to-noise ratio (PSNR), average delay, reachability, and control overhead. As proven by the results of the performance evaluations in this study, multi-path routing is better than single-path routing in terms of reliability. On the other hand, at high traffic loads, multi-path routing may perform worse in terms of delay due to its associated overhead.

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1. Introduction

Wireless multimedia sensor networks (WMSNs) is a new major research topic in academia as a result of the expectations of multimedia data producing wireless sensor nodes such as higher bandwidth demands, higher energy usage, and strict quality of service (QoS) requirements. The applications of WMSNs are used in many different areas, including surveillance and target tracking, advanced healthcare systems, industrial process control systems and intelligent traffic control [1].

In order to meet the QoS requirements of multimedia traffic, many WMSN applications need custom wireless sensor network (WSN) solutions. Most of the research efforts in WSNs have been motivated by the need for reducing energy consumption. However, both reliability and communication delay requirements of WMSNs have not

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http://dx.doi.org/10.1016/j.adhoc.2014.02.008
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been the main concern of WSNs. Therefore, QoS-aware routing solutions are needed to meet application-specific requirements of WMSNs. The analysis and design of a solution for image transmission in WMSNs are the main issues addressed in this paper. The major communication challenges for realization of QoS-aware routing in WMSNs can be outlined as follows:

- ***Energy consumption:*** Since multimedia applications may produce high volumes of data, energy consumption is more critical compared to traditional WSNs.
- ***Application-specific QoS requirements:*** Multimedia applications may have different requirements with respect to delay, reliability, and energy efficiency, which necessitate efficient routing solutions addressing diverse QoS requirements.
- ***Resource constraints:*** WMSNs are restricted by energy usage, memory and processing power because of their typical characteristics. Generally, limited node resources result in decreased QoS-awareness in WSNs and cause challenging problems [2,3]. Thus, routing solutions for WMSNs need to satisfy application-specific QoS requirements using these limited resources [4].
- ***Variable link capacity and packet errors:*** Characteristics of wireless link quality changes over time and space, hence high bit error rates are observed in communication. Therefore, capacity and delay vary frequently and this makes QoS a challenging task [4].
- ***Dynamic network connectivity and topologies:*** In WMSNs, distribution of sensor in the network and their connectivity may change over time due to link failures and sensor failures. Hence, to balance the trade-offs among available energy resources, reliability and latency requirements, adaptive communication protocols are required [4].

To address the abovementioned challenges, a novel approach is proposed for image transmission over WMSNs. By assigning different priority values to different parts of an image, high priority and accordingly high reliability are provided to high-priority data traffic. To realize this, data packets of an image file is divided into two classes and in this way different reliability values are set for each class. Different from the well-known routing protocol MMSPEED [5] which uses multiple speed layers to satisfy deadline requirements, the proposed approach uses a single speed layer to perform differentiation totally in reliability domain. By reducing total quality of an image without losing its important parts, energy consumption, resulting from redundant paths, is reduced.

To prove the efficiency of the proposed approach, the performances of QoS-aware single-path routing and multi-path routing protocols have been investigated for image transmission in WMSNs. The evaluated routing protocols offer three main functionalities, i.e. link-quality estimation, multi-path selection and prioritization, to meet reliability and delay requirements of image transmission applications, Comparative performance evaluations in terms of PSNR, average delay, reachability, and data and control packet overhead have been carried out in order to prove the efficiency of the evaluated routing protocols for image transmission. Although the results of the performance evaluations prove that multi-path routing is more reliable than single-path routing, multi-path routing performs worse than single-path routing in terms of average delay when network traffic load is high due to its associated overhead. Two main contributions of this study can be summarized as follows.

- Comparative performance evaluations of single-path and multi-path routing approaches for image transmission have been conducted in order to compare important QoS metrics, such as PSNR, average delay, reachability, and data and control packet overhead.
- The use of image prioritization for WMSN-based image transmission applications is proposed both to address energy efficiency requirement and to provide high reliability. In this regard, WMSN-based image transmission has been argued along with image prioritization from the point of reliability and communication delay.

The remainder of this paper is organized as follows. Section 2 presents a detailed review of single-path and multi-path routing protocols that can be used for WMSN-based image transmission. Section 3 explains performance metrics used in this study and presents simulation results. Section 4 highlights open research issues. Finally, the paper is concluded in Section 5.

2. Related work

In multi-hop networks, paths between source nodes and the sink can be determined by using hop count, a typical metric. However, in multi-hop wireless sensor networks, radio interference, antenna shape and orientation, distance and environmental factors may vary during the lifetime of a wireless sensor network and all of them affect link quality between pairs of sensor nodes. Although the locations of nodes in the network are fixed and every node is configured with the same transmit power, environmental variations result in asymmetric links between nodes and connectivity between nodes change [6]. In WSNs, single-path routing protocols try to estimate link quality and these protocols use link quality to find the best optimum path. Generally, this way is one of the most promising approaches to provide reliability in single-path routing. On the other hand, recent studies show that multi-path routing is better than single-path routing in terms of reliability. In other words, multi-path routing gives more probability to achieve packet reachability with the use of redundant paths to the destination.

Although multi-path routing offers advantages like reliability, its energy efficiency is questionable. Recent studies on WSN routing algorithms generally focused on energy efficiency to increase the lifetime of the network. On the other hand, there are many applications including mission-critical ones which do not only need energy efficiency they also need reliable and delay-sensitive routing [7]. In this section, single-path and multi-path routing protocols are organized in different subsections, and their features and distinct advantages and disadvantages are presented.

2.1. Single-path routing protocols

In this subsection, single-path routing approaches are reviewed based on their distinct features.

2.1.1. Reactive vs. proactive routing protocols

Single-path routing protocols can be divided into two main categories: reactive routing protocols and proactive routing protocols. SPEED [8] is one of the best examples of reactive routing protocols. SPEED is designed to support real time communication by minimizing end-to-end delay. Instead of using routing tables, each node makes localized routing decision by means of geographic location information about its neighbors. Packet progress speed is evaluated by each node using distance and delay and the packet is forwarded to node whose speed is higher than the pre-defined speed. Relay ratio is used for checking whether a packet is to be dropped or relayed when desired speed requirement is not satisfied. If generated number is higher than relay ratio then the packet is dropped. If congestion occurs or desired next hop node is not found, a message is sent back to the source nodes in order to start new routing. SPEED does not provide any guarantee regarding packet reliability [8].

Different from SPEED, its successor, energy efficient SPEED can be classified as a proactive routing protocol. It takes residual energy of nodes into account in routing and tries to find energy-efficient paths during real time communication. Routing is based on three metrics; delay, energy and speed. This protocol considers energy as a QoS metric but reliable communication is not the objective of this protocol [9].

Another proactive single-path routing protocol for real time data traffic, an energy-aware routing which takes both energy and delay into account to find an optimal path is proposed in [10]. This protocol selects the best path according to path cost calculated by a cost function. End-to-end delay and energy consumption are used to calculate the cost function. Transmission delay and queuing delay are used to calculate the end-to-end delay. This protocol tries to minimize transmission delay by using neighbor discovery algorithm.

2.1.2. QoS-aware single-path routing protocols

Energy and QoS-aware routing protocol proposed by Akkaya and Younis takes multiple network routes by using distance between nodes, remainder energy levels of nodes and error rates into account [11]. It uses a class-based queuing system to provide best-effort and real-time traffic at the same time. Service sharing for real-time and non-real time is supported by this class-based queuing. For both traffic types, required share of bandwidth is provided by Weighted Fair Queuing (WFQ) at every node. Limited scalability is a disadvantage of the protocol due to the calculation of multiple routes, although it provides guarantee for maximization of real time throughput within best effort transmission [11].

EARQ [12] is energy-aware routing protocol that offers real time and reliable communication for industrial WSNs. Energy cost, delay and reliability of a path are estimated by relying on information received from neighbors. Estimated values are used for probability calculation and a path is selected randomly according to the calculated probability. Therefore, sometimes optimal paths are not selected due to this strategy. On the other hand, random selection provides distribution of energy consuming. Real time delivery is accomplished by selecting some paths according to the packet delivery time of path before deadline. Also, redundant packets can be sent from an alternate path to provide reliability [12].

2.2. Multi-path routing protocols

MMSPEED, a multi-path and multi-speed routing protocol, takes reliability and timeliness into account and provides end-to-end QoS with localized decision at each intermediate node without end-to-end path recovery and repair [13]. Multiple speed layers are used to classify packets relying on their required delays. Intermediate nodes can change their speed by selecting different speed layer if possible to meet their deadline requirement. For reliability, each node sends received packets to subset of neighbors to satisfy required reliability value of packets. Nevertheless, MMSPEED fails to consider energy issues due to packet route determination and redundant paths [5].

EAMMSPEED uses an energy-aware packet delivery mechanism to provide QoS guarantee in WSNs [14]. It checks energy level of the next node while choosing the forwarding path. This is achieved by using beacon messages that give the information about the position, remaining energy level of the node. As a result, EAMMSPEED protocol makes a combination of QoS guarantees of MMSPEED with energy information of sensor nodes [14].

ReInForM [15] was designed to solve end-to-end reliability problems. Multiple copies of the packet are sent along to multiple paths from source to destination to make possible data delivery with the desired reliability. Number of paths required to satisfy reliability is controlled by dynamic packet state which relies on local knowledge of channel error rate and topology. ReInForM does not consider energy [15].

MPDT distributes workload equally among nodes in order to extend lifetime of WMSNs [16]. It operates in two phases: route set up phase and data transmission phase. Route set up phase discovers the multi-path route and data transmission phase selects the data to transmit in multiple paths. The nodes are selected by controlling the remaining energy in the nodes [16].

Reliable, Real-time Routing protocol (3R) takes both multi-path and time-constrained routing into account [17]. 3R claims that transmission delays can be reduced in WSNs by supporting paralleled transmission. This protocol uses Packet Reception Rate (PRR) estimations to calculate the necessary number of forwarding paths in order to ensure a certain reaching probability. Simulation results show that the 3R can decrease delays and increase reliability within high energy consumption.

REAR is an energy-efficient routing protocol which takes energy levels of sensor nodes into consideration before making a decision for routing paths. It uses a mechanism based on a messaging technique which is called as multi-path route request message (MREQ) to decide the routing path. MREQ message is broadcasted from source node to the other nodes in the network and the nodes forward MREQ message to the next nodes by checking their remaining energy levels. The nodes sending the MREQ message quicker are the ones that have higher energy levels and this criterion will make them selected for the routing path from source node the destination node [18].

EQSR [3] is an energy-efficient and QoS-aware routing protocol that takes into consideration of the energy level of sensor nodes, available buffer size and signal to noise ratio (SNR) in order to decide the best next hop. Its goal is to minimize energy consumption to increase network lifetime, keep the end-to-end delays of high important traffic packets acceptable value to achieve service differentiation in timeliness domain and increase packet reachability by using redundant data. Also, Forward Error Correction (FEC) technique is used by the protocol to recover node failures without flooding [3].

2.2.1. Why multi-path routing protocols?

In single-path routing, protocol is designed to discover and use single-path between a source and a sink. However, multi-path routing provides multiple paths between the source and the sink. In the following, the advantages and disadvantages of multi-path routing are briefly discussed.

The advantages of multi-path routing can be listed as follows:

- ***Load balancing:*** Balancing network traffic load can be possible by splitting the traffic across multiple paths.
- ***Reliability and Fault tolerance:*** Reliability can be defined as the probability that packets arrive from the source to the destination successfully. Multi-path routing can be used to improve reliability by sending multiple copies of data with different paths [19]. The receiver node will get the packet, if one of the replicated packets is received successfully.
- ***Highly aggregated bandwidth:*** Single-path routing may fail in proving required bandwidth. But, multi-path routing can provide the required bandwidth by employing multiple paths for transmission.

The disadvantages of multi-path routing can be listed as follows:

- ***Route coupling:*** WSN uses shared wireless channel to communicate. Therefore, if transmitting node keeps shared wireless channel busy, neighboring nodes are blocked from receiving data. While interference may cause degradation of quality of neighboring transmission, several metrics to estimate self-interference between different paths have already been proposed [20]. Route coupling can be explained as, in multi-path routing, transmission may interfere because of some nodes may be in the transmission range of others, even if the routes are node-disjoint paths. Route coupling shows that node-disjoint routes are not enough to improve performance [21].
- **Increasing end-to-end delay and network load:** In multi-path routing network, traffic is loaded abnormally because of redundant data packet and their control packets or simultaneously sending packets and their control packets. This high loaded traffic increases end-to-end delay of transmitted packets.

2.2.2. Constructing several paths based on routing metrics

Multi-path routing protocols reviewed in the previous subsection can be divided into two categories. Protocols in the first category transmit different packets to the destination though different paths. On the other hand, protocols in the second category transmit multiple copies of the same packet to the destination though multiple paths to improve network reliability. Although this approach improves network reliability and supports packet prioritization, it may lead to contention and congestion in the network.

Multi-path routing protocols can use several parameters, such as residual energy levels, end-to-end delay, link reliability, wireless channel error rate, network topology and available bandwidth, as routing metrics (see Table 1).

Although all the studies reviewed in this section provide valuable insights and foundations about WMSNs, they mainly aim to achieve energy efficiency or reliability objectives and do not study image transmission challenges in WSNs. In this paper, the performance of QoS-aware single-path routing and multi-path routing protocols has been investigated for image transmission in WMSNs.

3. Performance metrics and results

This section mainly focuses on performance evaluations of single-path and multi-path routing protocols. For the performance evaluations, MMSPEED has been preferred due to its ability to use many flows for differentiation on reliability and timeliness domain. Different from MMSPEED, the proposed approach uses only one flow and tries to differentiate one flow in reliability domain, i.e., instead of sending many images with different reliabilities, an image is divided into two different packet classes and sent in one flow. By means of image packet prioritization provided by the proposed approach, an image file is divided into different parts and high-priority parts take superiority in the network traffic.

3.1. Simulation specification

In this study, we have used J-SIM network simulator [22] to perform simulations. J-SIM is a Java-based open-source object-oriented library for discrete time process oriented simulations and dual language simulation environment written in Java. J-SIM supports script interfaces which can be TCL, Python and Perl for simulation scenarios. Our simulation scenarios are prepared via TCL scripts.

In this study, we have used two different routing protocols in our experiments; reliable multi-path routing

Table 1
Comparison of some of QoS-aware routing protocols.

	SPEED [8]	Energy and QoS-aware routing protocol [11]	MMSPEED [5]	Energy-aware MMSPEED [14]	Multimedia-aware MMSPEED [13]
QoSMetric	End-to-end delay	End-to-end delay	Delay and reliability	Delay and reliability	Delay and reliability
Energy-aware	No	Limited	No	Yes	No
Location-aware	Yes	No	Yes	Yes	Yes
Scalability	No	Limited	Yes	Yes	Yes
Service differentiation	No	No	Yes	Yes	Yes

protocol and reliable single-path routing protocol. We have also chosen one of two classes for each packet; low priority class and high priority class. We have used "Lena" test image and assigned high priority classes for its important part as shown in Fig. 1 in which the posture of the picture is captured with lines.

Simulations have been performed in three different scenarios;

- In the first scenario, all packets are assigned to high priority class.
- In the second scenario, the packets which represent important part of an image are assigned to high priority class. However, other packets are assigned to low priority class.
- In the third scenario, all packets are assigned to low priority class.

In all the scenarios, high priority value is set to 0.7, low priority value is set to 0.2, and deadline is set to 2.0. All the scenarios are repeated multiple times for different number of sources: 2, 4, 8, 12, and 16. Simulation parameters are listed in Table 2.

3.2. Performance metrics

In this study, we have evaluated average delay, reachability, PSNR and delay-bounded PSNR as performance metrics of all the scenarios for each protocol. Also, total numbers of data and control packets are calculated. Detailed explanation of the performance metrics are given below.

- ***PSNR:*** PSNR value presents ratio of maximum possible signal power to the corrupting noise power that affects the representation of an image. Reasonable PSNR value of an image should be 20 dB at least. We have calculated two different PSNR values for each case. First PSNR value is calculated for the whole image. The other PSNR value is calculated for only important part of the image.

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2 \quad (1)$$

PSNR is calculated by using MSE (Mean Squared Error) value of the two $m \times n$ images.

$$PSNR = 10.log_{10}\left(\frac{MAX_I^2}{MSE}\right) \quad (2)$$

MAX_I is the maximum possible pixel value of the image. When the pixels of the image are represented using 1 bit, this value is 1 but if they are represented with 8 bit, then this value equals to the 255. Hence, general formula of the maximum possible pixel value is $2^b - 1$.

- ***Delay-Bounded PSNR:*** Delay-bounded PSNR can be used to observe the effect of real-time delay bounds on reliable communication [19].
- ***Average Delay:*** Average delay is average transportation time of all transmitted data.
- ***Packet Reception Rate:*** Packet reception rate is the ratio of number of successfully transmitted packets to total number of transmitted packets.
- ***On-time Reachability:*** On-time reachability is packet reception rate of some packets which are successfully transmitted to the destination before the deadline.
- ***Control Packets:*** Control packets consist of MAC layer control packets, location update packets and back-pressure packets. MAC layer control packets are ACK, RTS, CTS and retransmission RTS packets.

Fig. 1. (a) Lena test image, (b) the important part of Lena test image.

3.3. Performance results

PSNR values have been calculated for both the whole image and the important part of the transmitted image. They are named as Total PSNR and Partial PSNR, respectively. Fig. 2a shows total PSNR values and Fig. 2b shows partial PSNR for all routing protocols. As it can be seen in

Table 2
Simulation environment settings.

Node number	100
Terrain	200 m × 200 m
Radio range	40 m
Packet size	256 Bytes
Traffic	CBR
Mac protocol	CSMA
Channel model	Two-ray ground

Fig. 2a, there are two cases that produce acceptable total PSNR values. These cases are multi-path routing and single-path routing with the first scenario explained above. Here it is important to note that total PSNR calculation is made by using the whole image and the first scenario assigns high priority to all image packets. Although multi-path routing keeps its trend, single-path routing does not keep its trend and it becomes worse with the increase of number of source flows.

On the other hand, Fig. 2b shows partial PSNR values. As it can be seen in Fig. 2b, partial PSNR values are acceptable for four cases. These cases are multi-path and single-path routing with the first and second scenarios. Note that partial PSNR calculates packets of the important part of the transmitted image and we assign these packets as high priority for the first and the second scenarios. Furthermore, for partial PSNR and total PSNR, multi-path routing keeps its good trend (between 20 dB and 25 dB), while single-path routing becomes worse with the increase of number of source flows. Finally, reliability of multi-path routing is higher than reliability of single-path routing for highly loaded network traffic. It shows that increasing the number of paths also increases the probability of reachability.

Fig. 3a and b show that the prioritization of image packets makes similar effect on both delay-bounded total PSNR values and partial PSNR values. However, delay-bounded PSNR values of single-path routing are higher than multi-path routing. This difference can be explained as packet transmission time of multi-path routing is longer than single-path routing due to high traffic load. Hence, multi-path routing provides acceptable PSNR values until 8 sources.

Furthermore, delay bounded partial PSNR values of the first and the second scenarios are similar to each other. This can be explained by the probabilistic chance of high priority packets in mixed network. If only important packets are assigned as high priority like the second scenario, then they have more probabilistic chance to reach destination compared to low priority packets. This challenging

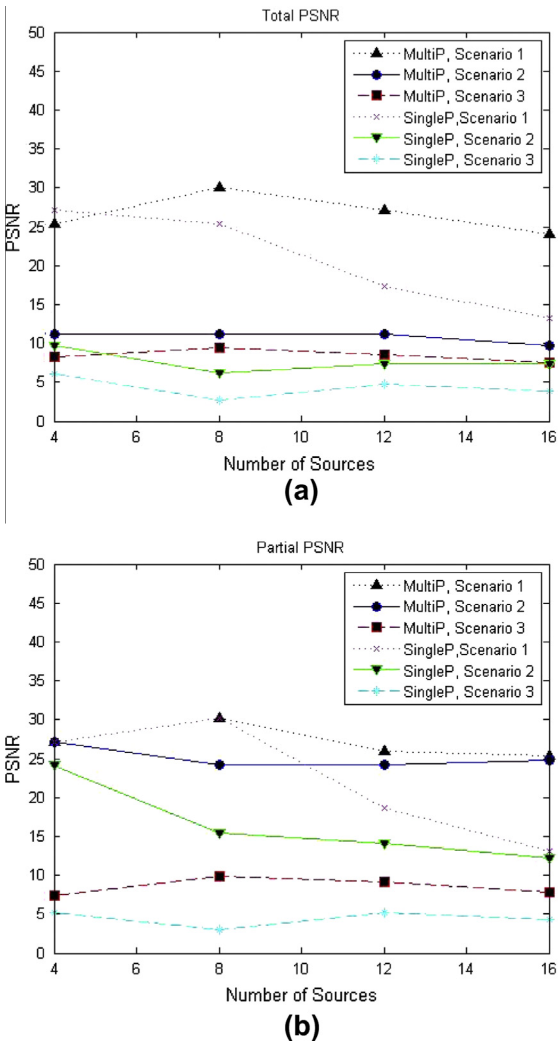

Fig. 2. (a) The average PSNR values of the whole image, (b) the average PSNR values of the partial image for four different flow numbers.

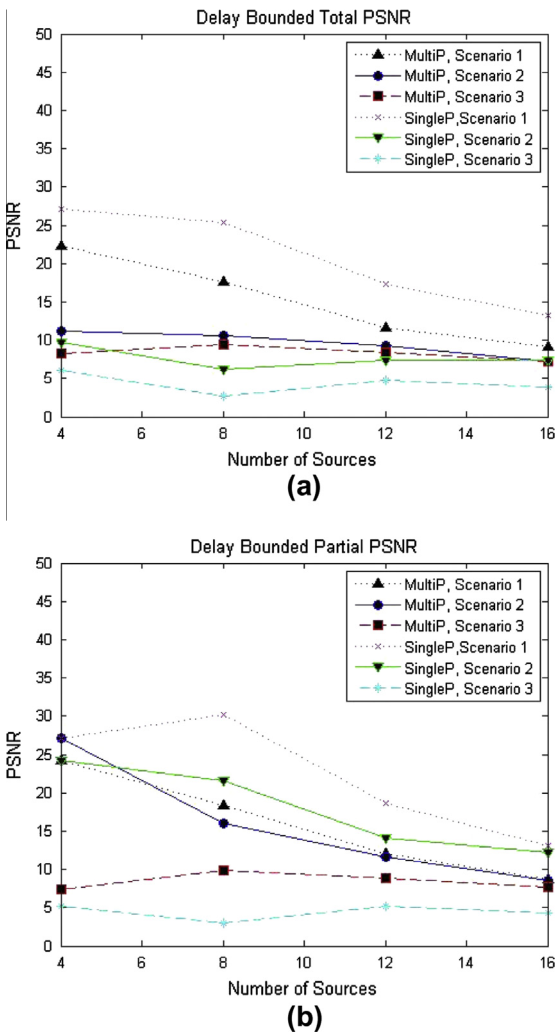

Fig. 3. (a) The delay bounded average PSNR values of the whole image, (b) the delay bounded average PSNR values of the partial image for four different flow numbers. Deadline is set to 2.0.

situation between the different priority packets makes high priority ones one step ahead. On the other hand, if all packets in the network are assigned as high priority, then there is no clear differentiation between packets of image parts.

The evaluations of total number of control and data packets show a clear differentiation for multi-path routing case and no differentiation for single-path routing case. This is because multi-path routing is keen to use redundant paths to achieve required probability values for packet transmission. Therefore, multi-path routing provides clear differentiation for the number of control packets and data packets. Hence packets, which are assigned high priority class tag, use more redundant paths than low priority packets in multi-path routing. This causes more control packet and data packet usage in the first scenario and average usage in the second scenario as shown in Fig. 4. Analysis of control and data packets shows us that image prioritization reduces number of control and data packets in multi-path routing. Also, we observe that image prioritization provides more flexibility and energy saving without loss of important image packets by means of using less redundant paths. On the other hand, there is no clear differentiation for single-path as shown in Fig. 4.

In Fig. 5, we observe that high traffic load causes increase in communication delay. Also, communication delays of multi-path routing are higher than delays of single-path routing. Because multi-path routing uses redundant paths instead of single-path and this multiple path usage causes more network load and increases network congestion and delay. This behavior of multi-path routing can also be observed in Fig. 4a and b.

Reliability provides clear differentiation for reachability for each protocol as shown in Fig. 6. The results are the same as expected results; the first scenarios have high reachability, the second scenarios have acceptable high reachability and the third scenarios have fair reachability. On the other hand, multi-path routing provides more reliability when traffic load is high. In detail, reliability of the second scenarios seems worse than the first scenarios. In addition, the second scenario gives enough PSNR value (between 20 dB and 25 dB, as shown in Fig. 2b) for the important part of the image.

As shown in Fig. 7, with 95% confidence intervals, the network cannot handle low deadline when network load increases, which call for adaptive congestion control mechanisms. However, delay distributions in Fig. 7 show that deadline 2.0 is enough for almost 16 sources network. Overall, we observe that in addition to QoS-aware routing algorithms, image packet prioritization can also be utilized in WMSNs in order to achieve moderate reliability, less energy consumption and higher Partial PSNR. The main results of performance evaluations can be summarized as follows:

- Overhead of control packets and data packets are reduced by prioritization of image packets for multi-path routing. PSNR value of important part of image preserved, although PSNR value of the whole image is decreased dramatically. We also observe that there is non-linear inverse ratio between the density of network traffic and communication delay.
- Reliability is conserved for both single-path routing and multi-path routing when network traffic is low. Reliability is differentiated for single-path routing and multi-path routing in a high loaded network and multi-path routing can achieve more reliable packet transmission in high loaded network scenarios.

When network traffic is highly loaded, single-path routing performs better than multi-path routing in terms of average delay due to high traffic load and associated overhead of multi-path routing. But, delay-bounded PSNR results are lower than delay-unbounded PSNR results, therefore this differentiation should be considered while comparing single-path and multi-path routing protocols in terms of average delay. Therefore, if QoS-aware routing protocols are used, delay-bounded PSNR values of high priority part of image might be preserved until network capacity is reached. On the other hand, multi-path routing is more consistent and keeps its trend according to the delay-unbounded partial PSNR results and this result shows

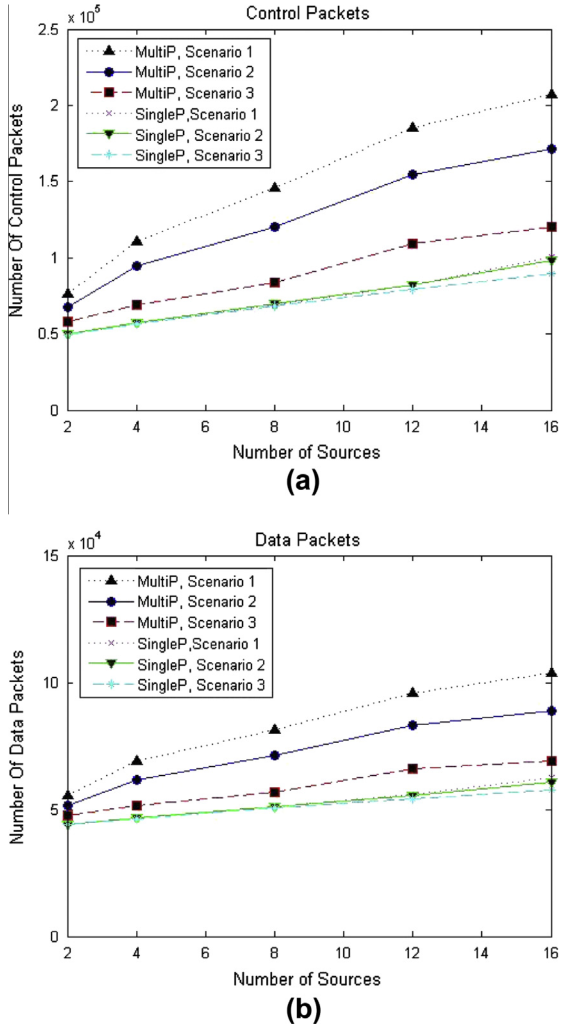

Fig. 4. (a) Number of control packets, (b) number of data packets for 5 different flow numbers.

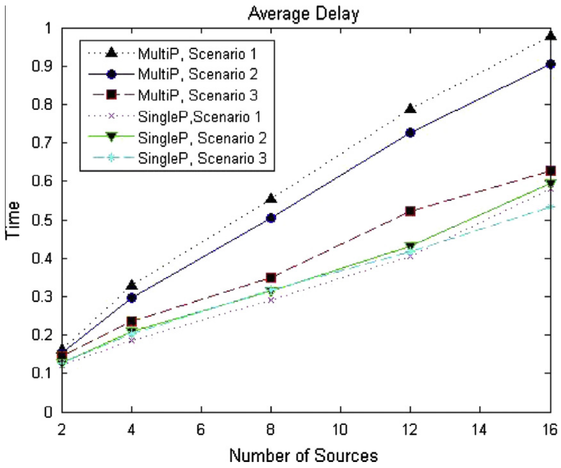

Fig. 5. Average delays of single-path and multi-path routing.

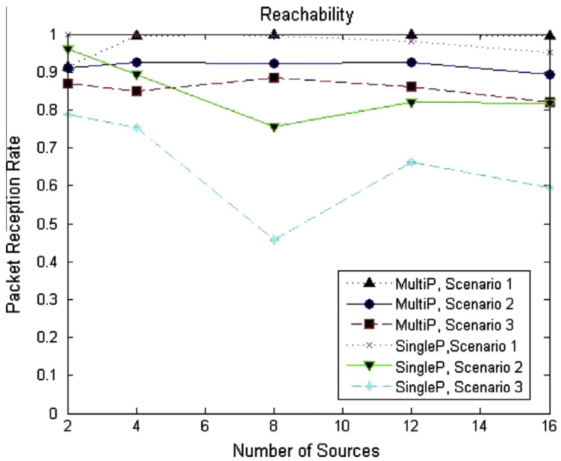

Fig. 6. Reachability (packet reception rate) values of three different scenarios within 2 protocols.

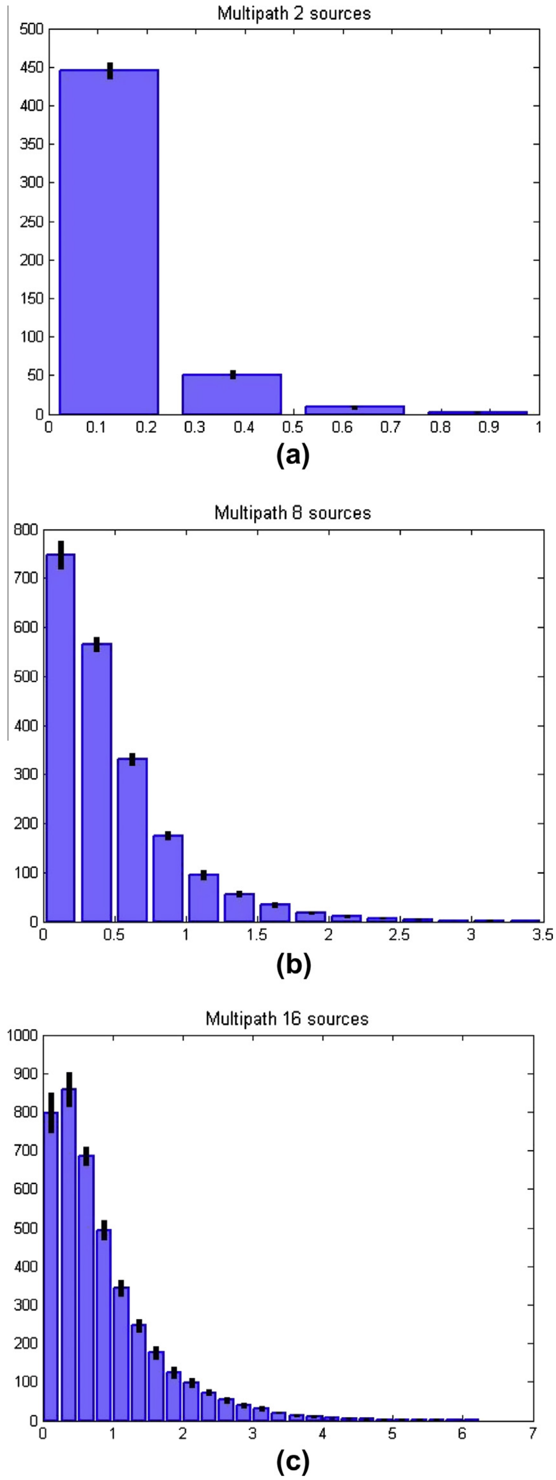

Fig. 7. Communication delay histograms with different number of sources, (a) multi-path routing with 2 sources, (b) multi-path routing with 8 sources, (c) multi-path routing with 16 sources.

that there is no clear differentiation on reliability of important part of images, but there is clear differentiation for control and data packet overhead. Hence scenario 2 (high priority is assigned to only important parts of an image file) is more desirable than scenario 1 (all packets have high priority).

4. Open research issues

Although, the existing single-path routing and multi-path routing approaches evaluated in this study can be employed in WMSN applications, a number of key issues still need to be explored. They are briefly summarized as follows.

- ***Use of Efficient Image Formats for WMSNs:*** Existing lossy and lossless image formats were designed for conventional PC-based applications. Considering possible packet errors and variable capacity of WMSN links, novel prioritization-based image formats with high-compression rates need to be developed. In addition, quality of experience (QoE)-based metrics for image formats can be initiated for this goal.

- ***Data Compression:*** It is well-known that wireless links exhibit varying characteristics especially in industrial zones. This cannot be completely eliminated. However, end-to-end data compression provided by node micro-controllers or specific hardware-based components can be effectively used to alleviate the drawbacks caused by the wireless links.
- ***Energy-Efficient Design and Energy-Efficient Protocols:*** Taking the resource constraints of sensor nodes into account, energy-efficient hardware and software solutions, such as adaptive transmission power control and dynamic duty cycles [23], and energy-efficient protocols must be key factors in emerging WMSN solutions.
- ***Mobility:*** Most existing solutions for WMSNs have either ignored mobility or assumed low mobility. Therefore, solutions for mobile WSNs need to be investigated. For this goal, internal low-cost GPS modules and/or novel location estimation algorithms can be utilized.
- ***Novel Routing Approaches:*** While the existing multi-path routing approaches can handle WMSN traffic, real-time video traffic requires specific geographical routing approaches such as the one proposed by Chen et al. [24].
- ***Commercial Availability:*** Although wireless sensor networks are well-established with a large number of commercial products, WMSNs still lack commercial off-the shelf solutions.
- ***Emerging Distributed Solutions for Efficient Image Transmission:*** Compared to WSN nodes, WMSN nodes have enhanced inherent capabilities which can efficiently be incorporated into WMSN-based image transmission applications [25].

5. Conclusions

Though WMSNs are attracting significant attention and their applications are increasing, specific techniques must be employed to meet associated QoS requirements of multimedia traffic and handle limited resources of WMSN nodes properly. In this study, a novel approach is proposed for image transmission in WMSNs. Using a set of different reliability values for image packets, a prioritization is realized and important parts of an image are assigned high priority. In this way, the important parts take priority during transmission. In order to evaluate the proposed approach, a set of comparative evaluations in terms of PSNR, average delay, reachability, and data and control packet overhead has been conducted to investigate the performance of QoS-aware single-path and multi-path routing protocols for WMSN-based image transmission applications.

In the performance evaluations, prioritization, link-quality estimation, and multi-path selection mechanisms were employed to address the requirements of WMSN-based image transmission applications. The results of the performance evaluations show that multi-path routing is more reliable than single-path routing and can be preferred to single-path routing. On the other hand, at the high load traffic, single-path routing performs better than multi-path routing in terms of average delay due to associated overhead of multi-path routing.

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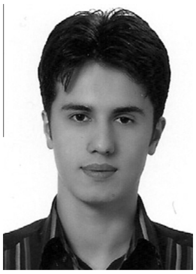

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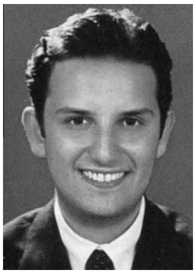

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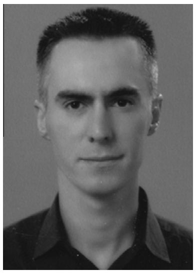

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