©2010 International Journal of Computer Applications (0975 – 8887)
Volume 1 – No. 6

Optimized Bandwidth Utilization for Real Time Applications in Wireless Sensor Networks

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ABSTRACT
Wireless sensor networks (WSNs) are special types of networks used in information gathering in military, industrial, and surveillance applications. Many such applications of WSNs require Quality of service (QoS) in terms of high bandwidth for real time applications including multimedia audio and video without much delay. These applications demand high packet delivery ratio and are extremely delay-sensitive. However, certain factors limit the ability of the multihop WSNs to achieve the desired goals. These factors include the delay caused by network congestion in the network, limited energy of the sensor nodes, packet loss due to collisions and link failure. In this paper, we propose an optimized bandwidth adaptation and utilization algorithm for real time applications in WSNs. The problem is formulated as linear programming (LP) together with specified constraints. Three types of applications (applications with strict delay requirements, applications with less stringent delay constraints and applications with delay tolerant capabilities) are considered for demonstration. Our claim is well supported with the simulation results carried on OMNET++ simulator.

Categories and Subject Descriptors
H.3.4 [**Systems and Software**]: Performance evaluation (efficiency and effectiveness).

General Terms
Algorithms, Performance, Design.

Keywords
Bandwidth consumption, real time applications, wireless sensor network

1. INTRODUCTION
Wireless Sensor networks (WSNs) are drawing much attention in the research community over the years due to wide variety of applications. One of the major concerns in WSNs applications is the design and development of a protocol to support real time applications. In this regard, consuming low power and increasing networks lifetime are important attributes of any routing protocol for WSN i.e. the protocol should ensure the connectivity in the network should be maintained for longer duration.

Sensor devices are equipped with miniature battery powered and wireless low-power transceivers capable of transmitting, receiving and processing video streams. These devices can compose wireless videos that will complement existing surveillance systems. These networks will have to support reliable, bandwidth efficient video transmission with minimum power consumption.

It is easier to design and model a real-time wired network system [1,2]. But, due to inherent problems of multihop WSNs, the design of a routing protocol, which is both QoS and energy aware, have many new challenges. The routing algorithms for ad hoc networks like AODV [3], DSR [4] can not be applicable in WSNs as these do not consider time deadlines, energy or congestion at the forwarding nodes while routing a packet to its destination. Also GPSR [5] maintains stateless information; which does not take into consideration, the congestion or the energy of the intermediate nodes.

In addition to these challenges, the high end-to-end bandwidth requirements of video communication usually can not be met in WSNs, when the traditional routing approach is used, leading to perceived video quality degradation. In order to meet the QoS requirements, an optimized bandwidth utilization approach can be adopted, where the video source (i.e., the server) delivers the data to its destinations via optimal paths, thereby supporting an aggregated transfer rate higher than what is possible with any path.

So keeping in view of the above challenges, we propose an optimized bandwidth utilization algorithm for real time applications. The problem is formulated as LP and algorithm to solve the same is proposed.

Rest of the paper is organized as follows: Section 2 discusses the related work, Section 3 formulate the problem along with different constraints involved, Section 4 describes proposed algorithm for optimized bandwidth utilization, Section 5 discusses the simulation and results, and finally section 6 concludes the article.

2. RELATED WORK
The key concerns in WSN are effective bandwidth utilization and and data dissemination for real time applications. In this regard GEAR [6] has been proposed. But it does not prioritize the real-time packets over non-real-time packets to ensure better packet delivery (in time) for deadline-driven traffic. Zorzi and Rao [7], suggest a geographic forwarding scheme where contention is done at the receiver's side. This scheme is not reliable because of possible packet loss in case of a collision. A better way of ensuring real-time packet delivery is flooding the network. However, flooding has extremely poor forwarding efficiency and results in lot of redundant transmissions, increased energy consumption, and hence decreased network lifetime. A better approach is suggested in [8], where a set of disjoint paths is maintained from source to destination over which the data is transmitted. This scheme also results substantial energy overhead, suffers from cache pollution and does not consider the time constraint of the packets.

Certain schemes like [9] require both GPS and GIS capability to find out the best route. SPEED [10] achieves the goal of forwarding the packets closer to the destination and takes into account, the presence of hot regions and congestion at forwarding nodes into its routing strategy. There are other strategies to choose an optimal path for real-time communication like minimal load routing [11], minimal hop routing, shortest distance path [12], etc. But these strategies do not specifically support the stateless architecture and the energy constraint of the sensor nodes.
Also multipath video transmission has been studied extensively in recent years [13-14]. The problem of minimizing delay among a video server and a client through optimum selection of multiple paths is addressed in [14]. In [15], a R–D optimization problem is solved using a Markov Decision Process (MDP). The authors studied the case of multiple servers containing data from the same requested video stream.A single path optimal packet scheduling mechanism for multiple description coded video sequences is presented in [16].

3. PROBLEM FORMULATION

Bandwidth in a WSN is a scarce resource and there are cases when the bandwidth required for transmission exceeds the available one. If the required rate for error free transmission is higher than the current available aggregate transmission rate then the sender decides which packets will be optimally dropped in order to adapt its current rate to the allocated one. The packets to be dropped are selected according to their impact on the overall bandwidth consumption. A combination of one or more packets may be omitted prior to the transmission by the source. Dropping a packet imposes a performance gap that affects not only the current packet but all the correlated packets also.

We have designed an algorithm for real time applications in WSN. More specifically theses applications are classified into below mentioned classes. The Base Station (BS) is adaptive w.r.t. the application and allocates the bandwidth accordingly.

Three types of applications are considered which are defined below:

RT^{D} : are those applications having strict delay requirements

RT^{LD} : are those applications that have less stringent delay requirements having variable size data packets on a periodic basis, multimedia applications. Because the size of the arriving packets is not fixed, connections are required to notify the BS of their current bandwidth requirements. As a result, this service causes a higher control overhead than that of first case.

RT^{DT} : are those applications that support delay-tolerant data streams and generate periodic variable-size data packets and require a minimum data rate. The applications include FTP, and those applications that have transmission rate limitations.

We have defined bandwidth metric B_M with the help of following functions which are defined in the bandwidth metric:

$d(\alpha,\lambda,b_i,\mu)$, $t(\alpha,\lambda,b_i,\mu)$ denotes delay and transmission rate of the packets, where λ is arrival rate, μ is the service rate, α is signal to noise ratio(SNR) and b_i is the allocated bandwidth.

Table1. Notations and their meaning

Also $E_t(S_i,S_j)$ .is the energy used in transmitting from S_i to S_j and $E_r(S_i,S_j)$ is the energy used in receiving the packet [17].

Notations	Meaning
B	Total bandwidth allocated for multimedia applications
U	Bandwidth reserved for RT^{D} applications
$b(RT^{D})$	Bandwidth required for RT^{D} applications
$b(RT^{LD})$	Bandwidth required for RT^{LD} applications
$\min(b(RT^{DT}))$	minimum bandwidth required for RT^{DT} applications
$\max(b(RT^{DT}))$	max bandwidth required for RT^{DT} applications
$l^{n}(RT^{DT})$	Level of adaptation

$$B\_M = 1-\left(\frac{1}{1+\exp[-d(\alpha,\lambda,b_i)-d^{req}]}+\frac{1}{1+\exp[-t(\alpha,\lambda,b_i)-t^{req}]}\right)+\frac{1}{E_t(S_i,S_j)+E_r(S_i,S_j)}$$

……………………………………………………………….(1)

Where d^{req} and t^{req} are the delay and transmission rate required for real time applications. So our objective reduces to

Maximize

$$\sum_i \{(B\_M\ b_i(RT^{D}))^{up} + (B\_M\ b_i(RT^{D}))^{down}\} +$$

$$\sum_i \{(B\_M\ b_i(RT^{LD}))^{up} + (B\_M\ b_i(RT^{LD}))^{down}$$

$\}+$

$$\sum_i \{(B\_M\ b_i(RT^{DT}))^{up} + (B\_M\ b_i(RT^{DT}))^{down}$$

}--(2)

Subject to following constraints

$$\sum_i b_i^{up} + \sum_i b_i^{down} \le B \text{ --(3)}$$

$$\sum_i b_i \le thr(RT^D) \text{ and } \sum_i b_i \le thr(RT^{LD})$$

$$\sum_i b_i \le thr(RT^{TD}) \text{ ---}$$

(4), where $RT^D, thr(RT^{LD}), thr(RT^{TD})$ is the minimum bandwidth thresholds required for each application.

$$\sum_i d(\alpha, \lambda^{up}, b_i^{up}) \le d^{(up,req)}$$

$$\sum_i d(\alpha, \lambda^{down}, b_i^{down}) \le d^{(down,req)} \text{ ------------------------(5)}$$

$$\sum_i t(\alpha, \lambda^{up}, b_i^{up}) \le t^{(up,req)}$$

$$\sum_i t(\alpha, \lambda^{down}, b_i^{down}) \le t^{(up,req)} \text{ ----------------------------(6)}$$

$$\sum_i b_i = b^{up,req}, \ \sum_i b_i = b^{down,req} \text{ ---------------------------(7)}$$

Constraint (3) specify that uplink and downlink bandwidth that is allowed to be allocated to a connection and it can not be greater than total bandwidth, and constraints (4) specifies the bandwidth threshold for three types of applications defined above, constraint (5) specifies the average delay for RT^D applications, while constraint (6) defines transmission rate for RT^{DT} applications while constraint (7) specifies bandwidth requirement for RT^{LD} applications.

4. PROPOSED SOLUTION

We have designed architecture for real time classification and scheduling as shown in Figure 1. Also an algorithm for optimal bandwidth utilization with defined constraints in equations (3-7) is proposed in Figure 2. The various components of the architecture are defined below which includes packet scheduling, buffer management and classifier.

Packet Scheduling

Packet scheduling is a part of traffic control in the networks and is referred to as the decision process used to choose which packet should be sent out first. In the connection-oriented network, connection admission control is deemed to resource reservation at the connection level; packet scheduling, on the other hand implements fair resource allocation in the packet level. The general packet scheduling algorithms include first in, first out (FIFO), round-robin, fair queuing, weighted fair queuing, etc. In FIFO, packets are forwarded in the same order in which they arrive at the transmitter. In the proposed solution, packet scheduling is performed according to the B_M defined in equation (1).

Buffer Management

Like network bandwidth, buffers are another network resource whose consumption should be controlled. The buffer management is to regulate the occupancy of a finite buffer queue. The buffer management makes the decision to admit or drop an incoming packet into the queue according to the state information, such as the content of the buffer queue, the flow to which the packet belongs, the number of packets in the flow current in the buffer queue.

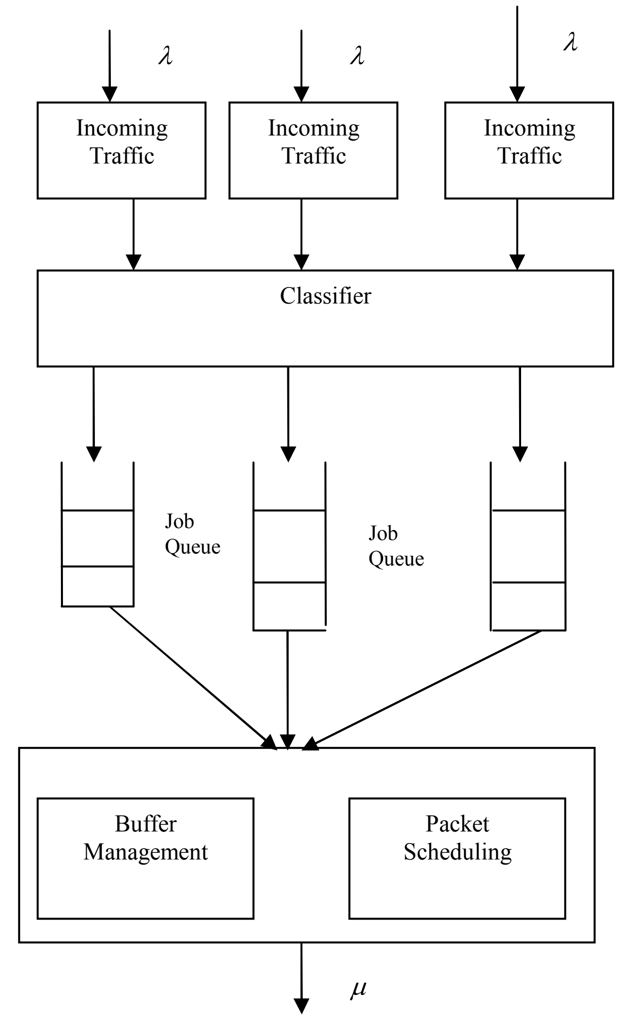

Figure 1: System Architecture for real time applications for classification and scheduling

Classifier

It is used for classification of incoming traffic with known defined rate as λ. It classifies the traffic according to their type as defined in Section3.

Now, we propose an algorithm for optimal bandwidth utilization as shown in Figure 2.

Case 1: For RT^D applications

1. Request from RT^D application arrives at the BS following Poisson distribution

2. Calculate the B_M defined in equation (1)

3. **If** (bandwidth currently allotted for all ongoing connections plus b(RT^D) ≤ total bandwidth allocated for RT^D , accept the request

4. **Else** reject the request.

Case 2: For RT^{LD} applications

5. Request from RT^{LD} comes at the BS.

6. Calculate the B_M defined in equation (1)

7. **If** (Total bandwidth set for all ongoing connections plus $b(RT^{LD})$ $\leq B - U$),

Accept the connection is admitted

8. BS sets aside $b(RT^{LD})$ bandwidth for the connection.

9. **Else** BS makes adaptation for the bandwidth set aside for all ongoing RT^{DT} connections

10. **until** (total bandwidth set aside for all ongoing connections plus $b(RT^{LD}) \geq B - U$).

11. **If** ((the currently set aside bandwidth plus $b(RT^{LD})$ is still $\geq B - U$ and (maximum degradation step $l^n(RT^{DT})$ of RT^{DT} connections has been reached)

12. Request for RT^{LD} connection is rejected

13. **Else** it is admitted by reserved $b(RT^{LD})$ bandwidth.

Case 3: For RT^{DT} applications

14. Request from RT^{DT} arrives at BS

15. Calculate the B_M defined in equation (1)

16. **If**(total bandwidth already set aside for all ongoing connections plus $\max(b(RT^{DT})) - l^n(RT^{DT}) \leq B - U$)

17. Accept the connection and allocate bandwidth for this RT^{DT} connection as $\max(b(RT^{DT})) - l^n(RT^{DT})$.

18. **Else** BS degrades the bandwidth set aside for all ongoing RT^{DT} applications

19. **Until (**current total bandwidth for all ongoing connections plus the bandwidth for the new RT^{DT} connection is not $\geq B - U$**)**

20. If this can be reached, the RT^{DT} connection is admitted with $\max(b(RT^{DT})) - (l^n(RT^{DT}))^{new}$, where

Figure 2: Algorithm for Optimized bandwidth Utilization

5. SIMULATION RESULTS

The network consists of 100 wireless sensor nodes distributed randomly over an area 50 m organized into different clusters. The selection of cluster head is done as defined in [17]. These sensor nodes are assumed to be capable of capturing, broadcasting live video sequences to a receiving point called BS. We have considered CBR traffic with payload size set to 512 bytes. Data packets are generated at the source at a rate of 1, 2, 3, 4 packets/s. Each simulation runs for 1000 s and there is no network partition during the course of simulation. We have compared the performance of the proposed system with QoS protocol proposed by Mahaptra et. al.[18]. In this scheme, the important resource namely as bandwidth consumption was ignored. We have compared the proposed scheme with [18] and analyze what will be the impact of bandwidth consumption on various network parameters namely as packet delay, network lifetime and packet scheduling.

Packet Delay

In Figure3, we have compared the packet delays for QoS aware scheme [18] and the proposed scheme. As shown in Figure, QoS aware scheme gives better results for simple applications. This happens because, when the network in not congested, least delay is achieved by forwarding the packet to the node closest to the destination. But as the traffic pattern changes, forwarding packets to destination results in increased congestion and more traffic delay in that area. But the proposed algorithm selects the path depending on application, thereby balancing the bandwidth in the network. This balancing helps to avoid hot regions in the network and reduces the delay for packets passing through the region i.e. for heavy traffic, proposed scheme gives improved performance.

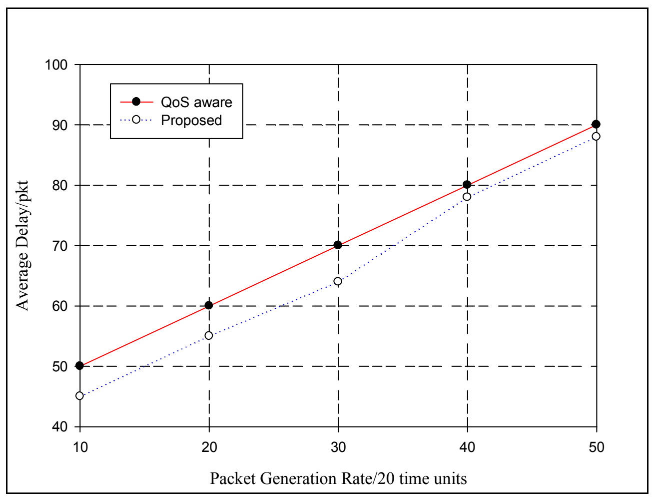

Figure3. Packet Delay in the Proposed and QoS Scheme

Network lifetime

Figure 4 compares the network lifetime for proposed scheme and [18]. QoS gives priority to energy; so it gives the performance as shown in Figure 4. The proposed scheme is also as efficient as QoS aware. The QoS aware scheme is able to balance node energy utilization and also accounts for the delay critical to real-time applications similar to the proposed scheme.

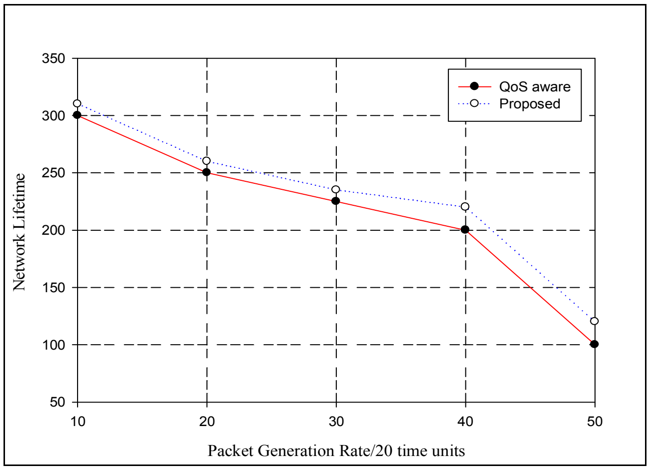

Figure4. Network Lifetime in the Proposed and QoS Scheme

Bandwidth Aware Packet Scheduling

Figure 5 shows the packet scheduling using proposed and QoS aware scheme[18], which does not consider the bandwidth consumption. The proposed algorithm utilizes the bandwidth model defined in (1) and assigns the importance of each packet according to its impact in the received data quality. Also the decision on which and how many packets will be dropped prior to transmission, whenever the transmission rate cannot meet the QoS requirements of the transmitted video is based on each packet's importance. The difference lies on the fact that the proposed algorithm implements a sensor bandwidth prediction routine, which allows the scheduling of the packet transmission or dropping to be decided on the bases of the bandwidth limitations of the channel.

Figure 5 also estimates the power that will be consumed by every node for all the paths in the network. It can predict whether a sensor node will be able to receive and transmit all the packets that will go through it in the next transmission window without consuming all its power and using maximum bandwidth. So the proposed scheme can control the life span of the sensor network by estimating the remaining bandwidth efficiency of each node in all the selected routes. Moreover, this approach reduces the resulted congestion of the application since it decides upon which and how many packets will be dropped due to transmission rate limitations and delay.

Also an analytical model is developed on the upper and lower bound for the loss of packets for each type of application in sensor networks which is given in Appendix.

6. CONCLUSIONS

In this paper, we have proposed an optimized bandwidth consumption aware algorithm for real time applications in WSN. Three types of applications are considered in WSN. The problem has been formulated as LP together with its constraints. The algorithm for optimal bandwidth is proposed using defined constraints. The performance of the designed algorithm is compared with existing solution w.r.t metrics like packet scheduling, network lifetime and packet delay. The results obtained show that the proposed scheme is better than the existing w.r.t. these metrics.

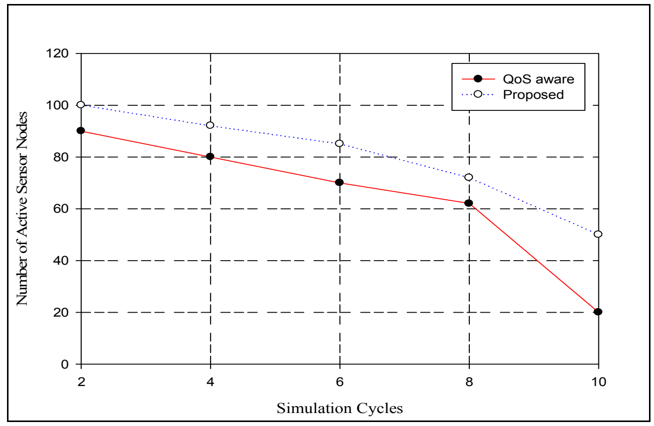

Figure5. Bandwidth aware Packet Scheduling in the Proposed and QoS Scheme

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APPENDIX: ANALYICAL ANALYSIS

In this section, we will estimate the level of adaptation for three types of defined applications as in Section 3 i.e. loss of packets are analyzed. We will find the lower and upper bounds of loss of packets for sensor node with different types of real time applications as defined in the Section 3. Firstly, the lower and upper bounds on the loss probabilities are calculated. Let p_1 and p_2 denote the lower and upper bounds on the loss probability. The upper bound is reached when there is no space in the output buffer. Therefore, the upper bound can be determined by the Erlang B formula (*M/M/k/k*) as follows:

$$p_2(k,\rho) = \frac{\rho^k / k!}{\sum_{i=0}^{k} \rho^i / i!} \text{--------------------------------(2)}$$

Where ρ is the total traffic intensity and k is the number of available paths from the sensor node.

The lower bound can be modeled by a *M/M/k/D* queue, where $D = D + k * B\_M$ is the maximum number of paths, and B_M is the number of cost metrics in terms of bandwidth available from each node to the destination. Therefore, the lower bound can be obtained as follows:

$$p_1(k,\rho,D) = \frac{\rho^D p_0}{k^{D-k} k!} \text{ ,…………………..(3)}$$

where $p_0 = \left(\sum_{n=0}^{k-1} \frac{\rho^n}{n!} + \sum_{n-k}^{D} \frac{\rho^n}{k^{n-k} k!} \right)^{-1}$ ..

It is assumed that the conservation law holds when the traffic intensity is high i.e. that the overall loss probability of the network remains the same no matter how many different types of applications there are and how these applications interact if the total traffic load remains the same.

The loss probability for a RT^D application is considered first since it has the highest priority of all other types of applications. The lower and upper bound are independent of other two types of applications and are determined only by its own traffic intensity. Then, the upper bound and lower bound for the RT^D applications can be obtained from equations 2 and 3 as follows:

$$p_2'(k,\rho') = \frac{\rho^{k'} / k!}{\sum_{i=0}^{k} \rho^{i'} / i!} \text{ and } p_1'(k,\rho',D) = \frac{\rho^{D'} p_0}{k^{D-k} k!} \text{, where}$$

$$p_0 = \left(\sum_{n=0}^{k-1} \frac{\rho^{n'}}{n!} + \sum_{n-k}^{D} \frac{\rho^{n'}}{k^{n-k} k!} \right)^{-1} \text{-------------------------(4)}$$

Similar expressions can be derived for other two types of applications using equations (1-4). These expressions will give the estimation on the upper and lower bound for packet loss at each sensor node and can be useful during adaptation.

Although this analysis can give quantitative guarantee on the loss probability of packets in terms of lower and upper bounds for different types of applications, but it is based on the assumption that each application is independent in its working from the others. Without this assumption, the loss probability of packets with higher priorities will still be affected by traffic with lower priorities, which will invalidate the above analysis.