A Novel Routing Protocol for (m,k)-firm-based Real-Time Streams in Wireless Sensor Networks

Bijun Li, and Ki-Il Kim
Department of Informatics, Engineering Research Institute
Gyeongsang National University
Jinju, Republic of Korea
{libijun, kikim}@gnu.ac.kr

***Abstract*—As the technology of multimedia applications in Wireless Sensor Networks (WSNs) is highly desired nowadays, how to guarantee real-time service becomes one of the biggest research challenges in this area. Even though lots of related works have been conducted to meet this requirement in several ways, the specific traffic model for multimedia applications has not been taken yet. It makes these new approaches not adaptable in real deployments. To solve this problem, in this paper, we model the real-time streams of multimedia applications with (*m*,*k*)-firm guarantee, using the firm real-time property it contains. A local transmission status indicator modified based on stream DBP (Distance-Based Priority), called L_DBP (local-DBP), is used to monitor the statement of delivery to the next hop and indicate network faults such as congestion and link failure during transmissions. By the contributions of both L_DBP and stream DBP, a novel geographic routing protocol is proposed to meet the requirements of real-time streams, by making routing decisions while considering timeliness and reliability features together. Simulation results reveal that (*m*,*k*)-firm is a good traffic model for multimedia sensor networks and the proposed routing protocol can efficiently avoid stream end-to-end dynamic failure, which is considered to be the main reason of QoS performance degradation.**

Keywords*- *real-time streams; L_DBP; (m,k)-firm model

I. INTRODUCTION

As the technology of wireless sensor networks (WSNs) develops, application-specific requirements on WSNs have gained significant importance in the last few years. Wireless Multimedia Sensor Networks (WMSNs) is one good example. The availability of using complementary metal-oxide semiconductor (CMOS) camera and small microphones in WMSNs make it possible to gather not only data information (like in WSNs), but also multimedia information from the surrounding environment [1]. However, given by the limited resources of nodes, such as memory, energy consumption, CPU performance, and unstable factors of wireless communication, it is more difficult to meet the requirements of WMSNs than traditional WSNs, since WMSNs must handle the special QoS (Quality of Service) requirements for multimedia applications [2] as well.

In WMSNs, packets do not reach the destination on time are not available in reconstructing the multimedia signal. They would be dropped during transmissions and considered lost. However, even if the loss rate of a multimedia stream is tolerable, it's possible that the quality of signal is not acceptable since too many consecutive packets are lost, leading to end-to-end dynamic failures and QoS degradation. To the best of our knowledge, most existing schemes are proposed to guarantee real-time requirements without considering this problem. SPEED [4] introduces a real-time communication protocol which provides desired delivery speed across the sensor networks through a combination of feedback control and non-deterministic geographic forwarding. However, it supports only soft real-time transmission because it doesn't take message deadlines of a real-time stream into account, which consequently leads to severe end-to-end dynamic failure. The protocol MMSPEED [5] provides a probabilistic QoS guarantee in both timeliness and reliability domains by multiple network-wide packet delivery speed guarantees and multi-path routing. It is supposed to guarantee hard real-time transmission but still has no scheme to avoid end-to-end dynamic failure. A multi-channel multi-path QoS-aware routing protocol to support high data rate for WMSNs is proposed in [6]. It makes routing decision according to the dynamic adjustment of the required bandwidth and path-length-based proportional delay differentiation. In [7], a routing scheme called PEMuR proposes the combined use of an energy aware hierarchical routing protocol with a video packet scheduling algorithm. A video distortion model is employed to enable the reduction of the video transmission rate with the minimum possible increase of distortion on each node, although the computation complexity of this model is quite high. *Hamdaoui* and *Ramanathan* proposed a scheduling policy called Distance-Based Priority (DBP) [8] to better service multiple real-time streams, each with its own (*m,k*)-firm guarantee requirement. Instead of assuming that all messages reach their destination in one hop, DBP-M [3] is extended to deal with the streams which their messages traverse more than one hop in reaching their destination, by providing a local-deadline to exploit the ability of many streams to tolerate occasional deadline misses. These scheduling schemes are not enough to handle real-time multimedia applications since only sink contains stream DBP and all intermediate nodes are transparent to it. So that each intermediate node cannot make correct routing decision to meet the (*m,k*)-firm deadline and QoS requirement.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0004102) and the MKE (The Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the NIPA (National IT Industry Promotion Agency (NIPA-2011-C1090-1031-0007).

In this paper, first we propose a local transmission status indicator called L_DBP, using (*m,k*)-firm model which is usually used for real-time message streams. The concept of (*m,k*)-firm is defined like that a real-time message stream is said to have an (*m,k*)-firm guarantee requirement if at least *m* out any *k* consecutive messages from the stream must meet their deadlines to ensure adequate QoS [8]. If this requirement cannot be satisfied, the stream may experience a *dynamic failure*, which is considered to be the main cause of QoS performance degradation. Applications in multimedia sensor networks require that audio/video signal should be sent as a stream of message packets across the network [10]. During transmissions, a stream DBP value is obtained by sink for indicating the signal quality, and the proposed L_DBP helps intermediate nodes to monitor the statement of delivery to the next hop, and indicates network fault such as congestion or link failure. Then, with the contributions of both stream DBP and L_DBP, a novel routing protocol is proposed to make routing decisions in real-time communications and efficiently implement fault management. Due to the inherent energy constraint and consideration of scalability, the proposed protocol uses geographic location to make localized routing decisions instead of approaches based on planar graph traversal [11] or limited flooding [12], though the design goal is not the same as previous location-based routing protocols.

The rest of this paper is organized as follows. In Section 2, the proposed protocol is mainly described. The simulation results are shown and analyzed in Section 3. The conclusion will be presented in Section 4.

II. PROPOSED PROTOCOL

The components of proposed protocol are organized and represented in Fig. 1.

In sensor networks, node location is more important than a specific node's ID since tracking applications only care about where the target is located, not the ID of reporting node [4]. It is natural to utilize geographic location in the proposed scheme to make a neighbor table on each node to participate in forwarding scheme. As shown in Fig. 1, the forwarding algorithm is the routing module responsible for making routing decisions, choosing the next hop to support real-time service and handling the congestion and link failure. The location information it uses and stream DBP value is provided by beacon exchange scheme. Single-hop delay estimation is the mechanism for upstream nodes to estimate the work load of each downstream node. The orphan node removal backpressure scheme is utilized to prevent "void" problem. The details of these components are discussed in subsequent sections, respectively.

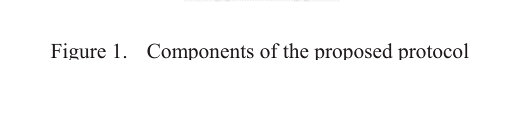

Figure 1. Components of the proposed protocol

A. Neighbor Beacon Exchange

Similar to other geographic routing algorithms, each node in the proposed protocol periodically broadcasts beacons to its neighbors. This periodic beacon is used to exchange location information among neighbors. In order to prolong the network lifetime that prevent some nodes from getting depleted much earlier than others, residual energy information is added in periodic beacons as well.

In addition to periodic beacon, three types of on-demand beacons are used to implement the functionalities. The single-hop delay estimation beacon and orphan node removal beacon are discussed in section *B* and *E*, respectively. Stream DBP beacons are sent from sink to source node during transmissions, after an initially defined interval, to help intermediate node make routing decisions in section *D*. We argue that the beaconing rate can be low when piggybacking scheme is used.

Based on the information provided by beacons, each node keeps a neighbor table and updates over time. The entries of this table are shown as below: (Neighbor ID, Position, EnergyLevel, EstimatedDelay, ExpireTime). The EstimatedDelay is obtained by Single-Hop Delay Estimation and the details are discussed in the next section (section *B*). The ExpireTime is set to be a standard RTT (Round-Trip Time) for packets transmission between a pair of nodes. For transmission status indicator L_DBP (section *C*), this ExpireTime is used to detect whether or not congestion or link failure occurs.

B. Single-Hop Delay Estimation

We use the delay estimation mechanism introduced by SPEED [4] to implement this functionality. Data packets passing is used for delay measurement. As a metric to approximate the work load of a node, this delay estimation is calculated at the sender side as shown. Formally,

$$Delay_{i,j} = RTT_{i,j} - T_{j,procACK} \quad (1)$$

where $Delay_{i,j}$ is the estimated single-hop delay between upstream node i and downstream node j. $RTT_{i,j}$ is the calculated round-trip time on node i, $T_{j,procACK}$ stands for the processing time of ACK on node j. The current delay estimation is computed by combining the newly measured delay with previous delays via the exponential weighted moving average (EWMA) [13]. Propagation delay is ignored. We use delay estimation instead of average queue size to measure load of nodes, since the shared media nature of wireless network, it's possible that the network is congested even if buffer occupancy is low [9].

C. Local Transmission Status Indicator L_DBP

The key components of this protocol are introduced in the following sections. In addition to stream DBP [8], the proposed protocol employs a novel scheme called L_DBP, which allows the intermediate nodes to make local investigation of delivery to the next hop. It can efficiently detect the status changes such as congestion and link failure, and help nodes handle the problem and prevent further degradation. Compared with the video distortion model in [7], L_DBP is considered to be more adaptable for multimedia sensor networks since its complexity is much lower, that it consumes less energy and computation resources, providing scalability in real implementations.

The functionalities of L_DBP and stream DBP are totally different. In this paper, stream DBP is calculated at sink, to show recent history of missed deadlines in the corresponding stream, while L_DBP follows the main idea of stream DBP that it can tell the distance to failure, in addition it makes nodes be aware of specific causes of deadline missing, such as congestion and link failure. The value of L_DBP is calculated as follow. Formally,

$$L\_DBP_i = k - m - c_j - f_j \qquad (2)$$

where L_DBP_i stands for the distance to failure on node i, k and m are set as the value of required (m,k)-firm; c_j and f_j denote the congestion and link failure level of downstream node j, respectively.

After an intermediate node receives the first packet, it starts a timer and forwards the packet to the next hop which has the least distance to sink among all downstream candidates in local neighbor table. Since multi-hop routing tends to increase the delay due to queuing and processing at intermediate nodes, long-range transmission is supposed to be effective in decreasing end-to-end delay by choosing the path with less number of hops. At the time it receives ACK from the downstream node, the experienced delay is set to be a standard RTT, namely ExpireTime as mentioned in section *A*, and stored into the corresponding entry of local neighbor table. Since nodes located near sink forward more packets than others, there is a possibility of congestion and link failure close to sink. Hence the ExpireTime is not the same for all nodes, but proportional to the number of hops to sink. Every time after an intermediate node forwards a packet, it will wait until the ExpireTime timeouts. The results of waiting can be categorized as below:

1) While upstream node receives periodic beacons from the downstream node during ExpireTime period:

   i) If it receives ACK, both c_j and f_j keep the same;

   ii) If not, f_j keeps the same while $c_j + 1$, which indicates congestion occurring.

2) While upstream node doesn't receive periodic beacons from downstream node during ExpireTime, then $f_j + 1$, which indicates link failure happened.

As a local transmission status indicator, the value of L_DBP demonstrates whether or not the current next hop can meet the QoS requirement of corresponding stream. The greater the value, the better condition this current stream has. In case of negative value, which shows deadline missing happening, L_DBP can distinguish congestion and link failure as different causes of deadlines missing in recent history. According to the values of c_j and f_j, node i can efficiently make local decision to solve the problem. The details are discussed in section *D*.

D. Geographic Forwarding Algorithm

In each node, the value of L_DBP and stream DBP, which is collected via beacons sent by sink, are used for the proposed forwarding algorithm as shown in Algorithm. 1.

Algorithm 1: Geographic Forwarding Algorithm

```
Pseudo-code executed by node i in each round
DBP(S(x)): DBP of multimedia stream x
L_DBPi: L_DBP of current node i
Nexti: next hop of node i
Distj: distance between node j and sink
Ni: number of nodes on neighbor table of node i
nj: number of candidate nodes
σi,j: estimated average delay between node i and node j
Pi,j: forwarding probability from node i to node j
-------------------- Step 1 --------------------
if DBP(S(x)) < L_DBPi then //local routing decision can't meet QoS
    L_DBPi = DBP(S(x))        //local adjustment
end if
if DBP(S(x)) >= L_DBPi then //local routing decision meets QoS
    if L_DBPi > 0 then  //in positive condition
        Nexti = arg_min{Distj}//choose the node closest to sink
                     j ∈Ni
    else
        if L_DBPi == 0 then  //prone to fault
            Nexti = arg_min{σi,j}  //change to node with smallest load
                         j ∈Ni
-------------------- Step 2 --------------------
        else
            if fj == 0 then  //only congestion occurs
                nj = min(|L_DBPi|, Ni)//confirm number of candidates
                for node j from 1 to nj+1
                    Nexti = arg_min{σi,j}
                                 j ∈Ni
                ∑1/σi,j += 1/σi,j
                end for
                for node j from 1 to nj+1
                    Pi,j = 1/σi,j / ∑1/σi,j  //forwarding probability in WRR
                end for
-------------------- Step 3 --------------------
            else
                if fj != 0 then  //link failure occurs
                    nj = min(|L_DBPi|, Ni)
                    for node j from 1 to nj +1
                        Nexti = arg_min{σi,j}
                                     j ∈Ni
                    end for
                end if
            end if
        end if
    end if
end if
```

STEP 1: In Step 1, first we compare the value of L_DBP_i with stream DBP to make sure if current local routing decision can meet QoS requirement at sink. If L_DBP_i is less than stream DBP, local adjustment is implemented that stream DBP will be used as metric. Otherwise, in positive condition, the first packet will be sent to the node closest to sink among all. As packets passing by, once L_DBP_i is equal to 0, which indicates the "prone to failure" status, upstream node would immediately change the next hop to the node with smallest estimated average delay, which means the lightest work load and highest reliability. This adjustment will prevent further degradation of stream DBP.

STEP 2: If local transmission status keeps getting worse, finally L_DBP_i would be less than 0. It means all downstream nodes on neighbor table cannot meet the requirement of current stream. To solve the problem, we have to know which fault occurs with downstream nodes via L_DBP. If f_j is equal to 0, apparently only congestion happened, and node i takes a load balancing strategy called Weighted Round-Robin (WRR) to mitigate the load on each node. The metric for re-choosing candidate nodes is also estimated average delay $\sigma_{i,j}$, and the number of candidates j is up to the condition of L_DBP_i, and routing probability for WRR is calculated based on $\sigma_{i,j}$.

STEP 3: If f_j is not equal to 0, the upstream node can infer that there's link failure happening in stream packets delivery. The best solution for failure management is to generate limited redundancy to downstream nodes. We also use estimated average delay $\sigma_{i,j}$ as the metric to find the nodes with lightest load and highest reliability.

This forwarding algorithm affords a local adaptation to the resource constraints of sensor networks and instability of wireless communication. Intermediate nodes are no longer transparent to transmissions; they take on the duty of local adjustment to meet end-to-end QoS requirement with the help of L_DBP and stream DBP. Simulation results show that this forward algorithm can efficiently decrease end-to-end dynamic failure under heavy work load and high link failure rate.

E. Orphan Node Removal Backpressure

Backpressure scheme is often used for re-routing or notification delivery. In the proposed protocol, we use backpressure only for removing the orphan nodes, which are defined as nodes without any downstream nodes in local neighbor tables, since these nodes may cause "void" problems in geographic routing schemes. Once an intermediate node updates its neighbor table and finds no downstream nodes left, it will use the backpressure beacons introduced in section *A*, to notify its upstream nodes to remove it from their neighbor tables. We argue that the overload can be low since the beacon rate is low and using of piggybacking scheme.

III. PERFORMANCE EVALUATION

The evaluation of proposed protocol is implemented on NS-2. In all simulations, we use uniform topology with the scenario of 100 nodes deployed in an area of 200m x 200m. The propagation model is set to be Two-Ray Ground, and protocols used on physical layer and MAC layer are set to be wireless-phy and 802.11, respectively. Radio range is set to be 40m for the nodes to transmit 64 bytes packets on the bandwidth of 1.5Mb/s. To evaluate the performance of proposed protocol, we use 2 scenarios. In the first one where several nodes are randomly chosen, to send periodic packets to the sink and generate cross traffic. The second one contains various link failures during transmission.

Evaluation results are presented as two sets: 1) packets end-to-end deadlines missing ratio, 2) stream end-to-end dynamic failure ratio. The former one is presented in many previous works that it considers the timeliness feature of individual packet, while the latter one is supposed to measure the QoS performance of real-time streams, which considers the connection between individual packets as well.

A. Packets End-to-End Deadline Missing

Fig. 2 and Fig. 3 plot the packets end-to-end deadline missing ratio of 3 different algorithms: SPEED, the proposed protocol with (3,5)-firm and (4,5)-firm guarantee requirements. The packets end-to-end deadline is set to be 50ms for all 3 algorithms.

The horizontal axis in Fig. 2 stands for the ratio of one specific stream to all streams in the scenario. The smaller the ratio, the heavier traffic load the nodes bear. Especially those which are close to sink, the probability of congestion happening is much high than other nodes. In Fig. 2 we can learn that streams using SPEED experience more than 20% end-to-end deadline missing of all packets when traffic ratio is less than 60%. Consider only delivery speed as routing metric, SPEED performs worse than proposed protocols even when the traffic load is not very heavy. Similar result comes from Fig. 3, that in a scenario where a certain degree of link failure happens, deadline missing ratio increases dramatically in SPEED since it lacks a link failure management. On the other hand, even under heavy traffic or unstable network condition, L_DBP works well to indicate the "distance to failure" and distinguish different faults; also based on both L_DBP and stream DBP, the proposed routing algorithm is more intelligent that it makes routing decisions or handles problems efficiently. The difference between (3,5)-firm stream and (4,5)-firm stream in both figures is that according to the mechanism of L_DBP, (4,5)-firm stream contains more strict requirement, so that the upstream node is more sensitive to the transmission status changes, and it will make more agile reaction to change the downstream node with better condition.

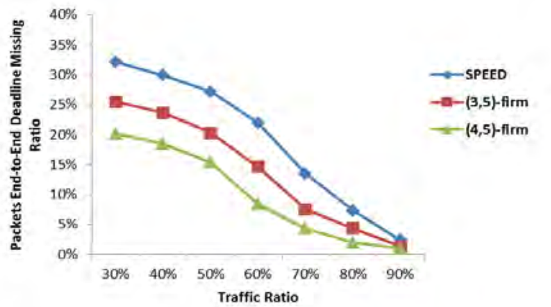

Figure 2. Packets End-to-End Deadline Missing Ratio

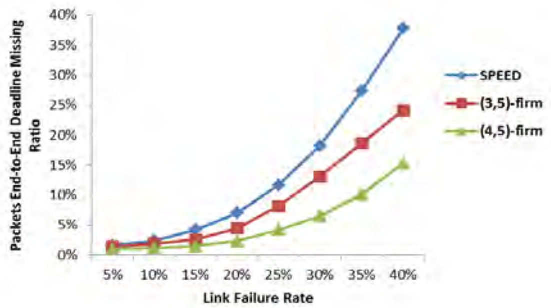

Figure 3. Packets End-to-End Deadline Missing Ratio

B. *Stream End-to-End Dynamic Failure*

In Fig. 4 and Fig. 5, we make a comparison of the stream end-to-end dynamic failure ratios, among 3 algorithms: SPEED, the proposed protocol with different deadlines of 40ms and 50ms, respectively. We give a (3,5)-firm guarantee requirement for all 3 algorithms to test their QoS performance guarantee.

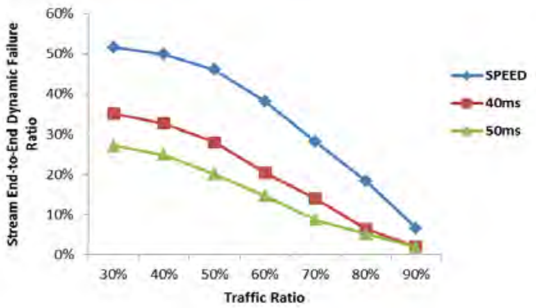

Figure 4. Stream End-to-End Dynamic Failure Ratio

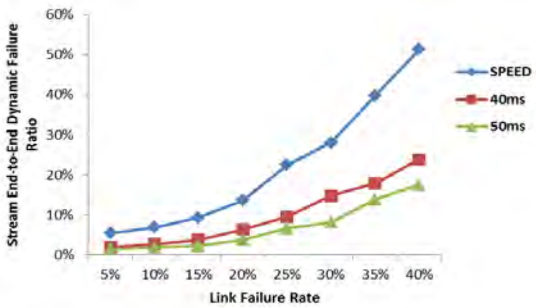

Figure 5. Stream End-to-End Dynamic Failure Ratio

In Fig. 4 and Fig. 5, simulation results show that the dynamic failure ratio is closely related to packet deadline missing rate. In addition, as we mentioned above, streams may experience end-to-end dynamic failures even if the loss rate is less than requirement. The significantly rising curves of SPEED in both figures demonstrate that without firm real-time requirement, it failed to apply good QoS performance in case of heavy traffic or prone to failure links. Together with stream DBP, the proposed L_DBP plays a very important role in packets transmission that it makes all intermediate nodes to be aware of local transmission status with next hop, and real-time stream quality at sink. We can also infer that the routing algorithm is effectively used in fault management schemes such as load balancing for congestion in Fig. 4 and limited redundancy for link failure in Fig. 5. This hop-by-hop local fault management helps to save time during transmissions. It could be highly desired by firm real-time stream applications. By distributing the duty of guarantee (*m,k*)-firm at sink to each intermediate node, L_DBP and stream DBP together make it possible to keep good QoS performance of real-time streams.

IV. Conclusion and Future Work

For application-specific sensor networks such as WMSNs, which have additional real-time requirements, the timeliness feature and end-to-end QoS requirement are difficult to be satisfied by current technology. The proposed protocol employs the (*m,k*)-firm to model the real-time streams, and also a local transmission status indicator called L_DBP to show the delivery statement of next hop. According to the information provided by L_DBP and steam DBP, a novel geographic routing algorithm can make local decision to handle the various network faults efficiently. This adaption capability makes it more functional in simulations, comparing to SPEED, a soft real-time routing protocol for sensor networks. Simulation results show that due to the contribution of each component of the proposed protocol, it performs better in both timeliness and QoS guarantee features with low end-to-end deadline missing ratio and low end-to-end dynamic failure ratio.

The future work will be focus on finding new metric for routing algorithm and new parameters for fault management.

References

[1] A. Sharif, V. Potdar and E. Chang, “Wireless Multimedia Sensor Network Technology: A Survey,” IEEE 7th Annual Int. Conf. Industrial Informatics Wales, p. 606, 2009.

[2] J. F. Mingorance-Puga, G. Macia-Fernandez, A. Grilo and N. M. C. Tiglao, “Efficient Multimedia Transmission in Wireless Sensor Networks,” IEEE 6th Annual EURO-NF Conf. Next Generation Internet France, p. 1, 2010.

[3] W. Lindsay and P. Ramanathan, “DBP-M: A Technique for Meeting End-to-End (m,k)-firm Guarantee Requirements in Point-to-Point Networks,” IEEE 22nd Annual Int. Conf. Local Computer Networks USA, p. 294, 1997.

[4] T. He, J. A. Stankovic, C. Y. Lu and T. Abdelzaher, “SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks,” IEEE 23rd Annual Int. Conf. Distributed Computing Systems USA, p. 46, 2003.

[5] E. Felemban, C. G. Lee, E. Ekici, R. Boder and S. Vural, “Probabilistic QoS Guarantee in Reliability and Timeliness Domains in Wireless Sensor Networks,” IEEE 24th Annual Int. Conf. INFOCOM USA, p. 2646, 2005.

[6] M. A. Hamid, M. M. Alam and C. S. Hong, “Design of a QoS-aware Routing Mechanism for Wireless Multimedia Sensor Networks,” IEEE Int. Conf. Global Telecommunications USA, p. 1, 2008.

[7] D. Kandris, M. Tsagkaropoulos, I. Politis, A. Tzes and S. Kotsopoulos, “Energy Efficient and Perceived QoS Aware Video Routing over Wireless Multimedia Sensor Networks,” Jour. Ad Hoc Networks, vol. 9, issu. 4, Elsevier B. V., 2011, pp. 591-507.

[8] M. Hamdaoui and P. Ramanathan, “A Dynamic Priority Assignment Technique for Streams with (m, k)-Firm Deadlines,” IEEE T. Comput. USA, vol. 44, issue 12, December 1995.

[9] C. Y. Wan, S. Eisenman and A. Campbell, “CODA: Congestion Detection and Avoidance in Sensor Networks,” ACM 1st Int. Conf. Embedded Networked Sensor Systems USA, pp. 266-279, 2003.

[10] I. F. Akyildiz, T. Melodia and K. R. Chowdhur, “A Survey on Wireless Multimedia Sensor Networks,” ACM Computer Networks: Int. Jour. Computer and Telecommunications Networking USA, vol. 51, issue 4, March 2007.

[11] B. Karp and H. T. Kung, “GPSR: Greedy Perimeter Stateless Routing for Wireless Sensor Networks,” IEEE 6th Annual Int. Conf. Mobile Computing and Networking USA, p. 243, 2000.

[12] G. G. Finn, “Routing and Addressing Problems in Large Metropolitan-Scale Internetworks,” Tech. Rep. ISI/RR-87-180, USC/ISI, March 1987.

[13] J. F. Kurose and K. W. Ross, Computer Networking A Top-Down Approach Featuring the Internet, 5th ed., Pearson/Addison Wesley, 2009, pp. 252-253.