QoS-Enabled Video Streaming in Wireless Sensor Networks

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Abstract

Recent advances in wireless communications technology and low-power, low-cost CMOS imaging sensors enable a new sensing modality employing ubiquitous distributed video sensing. In many video sensing applications multimedia streams are often required by the base station to provide detailed information of the target spot in the sensor field. However, limited bandwidth, unstable network environment, and data transmission interference prevent the large-scale deployment of such applications without new strategies for energy and data capacity management. In this paper we propose a dynamic path formation algorithm based on our data path throughput estimation model. Coupled with a distributed TDMA packet scheduling scheme, this path formation algorithm can establish throughput-aware video delivery path between source and destination. OPNET simulation results indicate that the throughput estimation is accurate and our proposed TDMA scheme is preferred for streaming applications. We also explore the use of distributed mobile base stations as an option to improve the egress of video data streams from the network.

Keywords – Wireless Sensor Network (WSN), Wireless Video Sensor Network (WVSN), QoS, Video Routing, Video Streaming, Throughput Estimation, Path Formation.

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1. Introduction

With the development of low power, low cost CMOS imaging sensors, scientists envision a great potential of multimedia streaming application for wireless sensor networks (WSN) in the area of homeland security, habitat monitoring and image-based monitoring and control. For these applications a sensor node can capture images, audio and/or video information, and send them in a compressed form to a consumer elsewhere on the network. A user need not wait for the download of the entire video sequence but instead can playback the content immediately once data begin to arrive at the receiver.

Today, many of the existing wireless video sensor network (WVSN) applications [2, 3, 4, 5, 6] are simply integrations of Internet video streaming solutions to the domain of WSNs. Some applications still rely on conventional wired video cameras. Others assume wireless communications but do not address scale-up to large numbers of video cameras nor the support of multiple streams.

One of the main obstacles for the large scale deployment of WVSN is the lack of mechanisms to manage contention among multiple source-to-destination video streams in the context of sensor network energy and communication constraints. Moreover, due to the hardware limitations of the video sensor node, such data paths are difficult to achieve required throughput for multimedia streams. In this paper we propose a path formation algorithm based on throughput estimation to construct throughput-aware video delivery path. We explore enhancing the performance of the video delivery over the WSN by isolating concurrent video streams to eliminate the path coupling interferences and efficiently distributing a limited number of mobile base stations to help relay video data. These mobile base stations have much higher communication and networking capabilities. Paired with our distributed packet scheduling scheme, the throughput of our data path is independent of the path length. Such path formation algorithm can be employed to create advanced routing protocol targeting for video streaming applications to facilitate stream data routing with low latency.

2. Throughput Estimation Model and Packet Scheduling Scheme

In this section, we introduce our TDMA-based packet scheduling scheme and the mathematical throughput estimation model for data transmission on a single path. We assume that (1) Radio range of each sensor node is identical; (2) A single radio channel is shared by all sensor nodes; (3) Simultaneous radio transmission within one node's radio range will cause packet collisions at the node; (4) Radio transmission outside the node's radio range will not interfere with the packet receiving process of the node.

A. Throughput Estimation Model:

We cluster sensor nodes along a data path into small concatenated groups. The size of each group is determined by the interference range measured in hop count of the sensor node and can be calculated by (1). For simplicity we let the interference range of a sensor node along a data path be one hop and therefore each group in our model contains three nodes with length of two hops as shown in Fig. 1. We propose a distributed TDMA-based packet scheduling scheme within each group to control the packet forwarding process and alleviate the negative effect of media access contention. This scheme eliminates the contention inside each group and allows nodes that are 3 hops away from each other to transmit data simultaneously such as A and D in Fig 1. Under our network radio model, the TDMA-based packet scheduling scheme achieves the pipelined data forwarding for the streaming application.

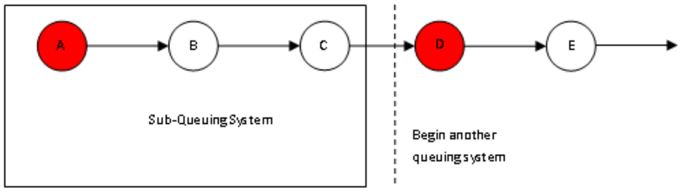

Figure 1. Illustration of sub-queuing system

$$\text{Group size} = \text{Interference range} + 2 \tag{1}$$

We model each group along the path as a sub-queuing system and notice that if there is one packet being forwarded inside the sub-queuing system, due to the shared channel assumption the arriving packet to the subsystem should be dropped since the packet is likely to be corrupted/interfered by the transmission inside the subsystem. If we assume the packet arrival process is a Markov renewal process then we can use G/G/1/1 queuing model to characterize our first sub-queuing system. Since the arrival process of the cascaded subsystem is the departure process of the prior subsystem, in order to understand the transmission process of the entire path, we characterize the departure process of each system.

We denote the following variables:

- S: service time of the k^{th} accepted packet in the subsystem
- A_i: Inter arrival time between the i^{th} and $(i+1)^{th}$ packet arrival
- D_k: Inter departure time between the k^{th} and $(k+1)^{th}$ accepted packet by subsystem

Since A_i are iid random variables and S is a constant due to our TDMA based scheduling scheme, D_k is therefore a series of iid. random variables expressed in (2). The departure process of each subsystem is also a Markov renewal process. Under this case we can model the rest of cascaded subsystems to be G/G/1/1 queuing models, and our data path is a cascade of G/G/1/1 queuing systems.

$$D_k = \begin{cases} A_n \ \ (S < A_n) \\ A_n + A_{n+1} \ \ (A_n < S < A_n + A_{n+1}) \\ \quad \quad \quad \quad \cdots \\ \sum_{i=n}^{n+l} A_i \ \ (\sum_{i=n}^{n+l-1} A_i < S < \sum_{i=n}^{n+l} A_i) \\ \quad \quad \quad \quad \cdots \end{cases} \tag{2}$$

Although the data path is consist of multiple cascaded subsystems, according to our analysis in [7], inter-departure time of the entire data path is identical to the inter-departure time of the first subsystem along the path. As a result, the data output process of the entire data path is independent of the path length and identical to the data output process of the first subsystem along the path.

We denote the CDF of the D_k as $F(t)$, $F(t)$ can be expressed in (3).

$$\begin{aligned} F(t) = \ & \Pr(D_k < t) = \Pr(S < A_n) * \Pr(A_n < t) \ + \Pr(A_n < S < A_n + A_{n+1}) \\ & * \Pr(A_n + A_{n+1} < t) + \cdots + \Pr\big(\textstyle\sum_{i=n}^{n+l-1} A_i < S < \sum_{i=n}^{n+l} A_i\big) * \Pr\big(\textstyle\sum_{i=n}^{n+l} A_i < t\big) + \cdots \end{aligned} \tag{3}$$

We denote the Laplace transform of $F(t)$ as $L(F,s)$. If $L(F,s)$ is second order differentiable, we can derive the expected inter departure time and its variance as (4), (5):

$$E(D_k) = -\frac{d[s * L(F,s)]}{ds}\bigg|_{s=0} \tag{4}$$

$$Var(D_k) = \frac{d^2[s*L(F,s)]}{ds^2}\Big|_{s=0} \quad (5)$$

B. TDMA Based Packet Scheduling Scheme:

We proposed a simple TDMA based packet scheduling scheme for our packet transmission. We assign each node inside a subsystem a data sending time slot. A count-down timer is activated once the first node of each subsystem begins forwarding a packet. The initial value of the timer equals to the product of the slot length and subsystem size (number of nodes in the subsystem). The first node of each subsystem is not allowed to accept packets during the activation period of the timer. Once a packet is forwarded by the first node of the sub-queuing system, a timestamp is logged in the packet. When the subsequent node (the second node in the subsystem) receives the packet, it adds the agreed slot length to the time stamp to get the time of the first node and therefore synchronize its time with the first node. The third node of the subsystem adds twice the slot length to synchronize with the first node of the subsystem and so on so forth. Each node in the subsystem is only synchronized to the first node of the subsystem. Such distributed synchronization scheme simplifies the implementation complexity of the network-wide synchronization and the usage of data packet for synchronization minimizes the synchronization overhead. The slot length can be either predefined by the source node and then propagates to all the sensor nodes along the path or it can be computed dynamically according to the quality of the links along the data path and updated periodically if the wireless environment changed dramatically.

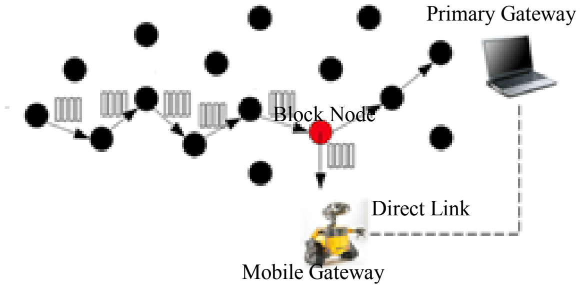

Figure 2. General Scenario

3. QoS Enabled Path Formation Algorithm

In this section, we present our QoS enabled path formation algorithm for video streaming applications over WSN. From the aspect of high-level illustration, our path formation algorithm can be divided into two steps as shown in Fig. 2. In step one, source node S initiates a path formation process to find a reliable path to primary gateway and meanwhile informs the gateway the location of the block node (Fig. 2) based on the available sensor node resources. In step two, the primary gateway deploys the mobile station to the block node location to bridge the data relay.

Path formation consists of finding a sequence of nodes (a path), n_s, n_1, n_2, ..., n_d from source node n_s to destination node n_d (primary gateway). This path should be inexpensive, free from loops, and should not interfere with existing stream paths. In the following we sketch a greedy algorithm that constructs paths in the presence of existing ones, finding paths when they exist. We assume that (1) each sensor node is aware of its location and the locations of the primary gateway and its neighbors'; (2) source node is aware of the throughput requirement (threshold) of the video stream. Based on throughput estimation model in Section 2, we decompose our path formation process into the following four basic tasks.

1) Task One: Data Path Set Up

We define two sensor node states for our path set up process: if a node is currently serving another stream or it is in the interference range of certain sensor node along certain existing stream path, the node is “occupied” by an active path, otherwise the node is “available” for constructing new data path. Our greedy data path set up process is analogous to [1]. A path request query is initiated by the source (n_s) and forwarded to the neighborhood. The query is intended to form a path P which is set of nodes n_s, n_1, n_2..., n_i, n_{i+1} , ...n_d from source to destination. The intermediate node n_i forwards the query to a node n_{i+1} in its neighborhood such that n_{i+1} minimizes geometric distance D(n_i, n_d) and meanwhile the node n_{i+1} is “available,” plus n_{i+1} is out of interference range of node n_{i-1}. Each intermediate node also caches information of the previous hop, next hop and distance from source to itself in terms of hop count. The process is repeated until the path request is received by the destination n_d. If there is a dead end during the path set up process, a similar detour algorithm as in TPGF [6] is performed to avoid network holes.

2) *Task Two: Clustering Nodes into Sub-Queuing Systems*

After receiving the request, the destination will send back a path acknowledgement to the source with information of the path length. Due to the broadcast nature of the wireless media, each sensor node appearing in the neighborhood of sensor nodes along the newly established path will overhear this acknowledgement and set their state to be “occupied.” These “occupied” nodes cannot be employed by other streams to deliver video. As a consequence, the interference between different streams is eliminated. As each sensor node knows exactly the hop count from the source to its self, and the size of the sub-queuing system is three under our assumptions, each sensor node could decide its system ID and location inside the system by applying the following equations:

$$system\ ID = hop\ count\ from\ source/3 \qquad (6)$$
$$system\ location = (hop\ cout\ from\ source) mod(3) \qquad (7)$$

The possible location value is in $\{0,1,2\}$. Value 1 indicates that this node is the first node of the sub-system. Value 2 indicates the second node of the small queuing system and 0 indicates the last node of the system.

3) *Task Three: Data Transmission*

Once the source receives the acknowledgement, it will take advantage of (2-4) to compute the average packet departure time of the data path and therefore by taking the inverse of the result the source node could calculate the data path throughput. If the resulted throughput satisfies the throughput requirement of the stream, the source node will send a notification packet to synchronize the sensor nodes along the path and begin sending out data using the proposed TDMA scheme. If not, the source node will send out free path signal to free the occupied nodes of the data path. .

4) *Task Four: Block Node Notification and Mobile Station Deployment*

Under some extreme scenarios the available data path between the source and the destination may not exist. Applying detour algorithm on these scenarios only ends up with a series of dead ends. Our sensor nodes cache a collection of routes to the corresponding dead end nodes. We choose the dead end node which is nearest to the primary gateway to set up our data path. The chosen dead end node broadcasts the location to its neighbors and this information will be flooded to the primary gateway. When the primary gateway receives the location notification, it will deploy mobile base station to the location to bridge the video data forwarding. We associate the deployment cost of mobile base stations to the distance between the station and the primary gateway. Since the block node is the nearest node to the primary gateway along the stream path with required packet departure rate, deploying mobile stations to these block node locations not only guarantees the data delivery throughput performance but also minimizes the deployment cost for each video stream. As soon as the mobile base station is on position, the block node will be informed and send out a "notification" message to the source node. The source then is informed and begins streaming data to the mobile base station.

4. Simulation Results

The success of our path formation algorithm is largely depended on the accuracy of our throughput estimation model and performance of our proposed TDMA scheduling scheme. In this section we examine these two critical components via OPNET simulations.

A. TDMA Scheme vs. CTS/RTS

We compare the performance of TDMA and CTS/RTS scheme in two different scenarios. In Scenario 1, the link utilization ratio is very low. The data source generates a packet with a size of 1024 bit every 5 seconds. The link transmission delay is 1 second. The results are shown in Fig. 3. In Scenario 2, we push the data rate higher approaching the optimum throughput of the data path. In our network model, the optimum data path throughput is roughly one third of the link capacity. The results are displayed in Fig. 4.

We observe that in the low link utilization scenario, both TDMA and CTS/RTS schemes can eventually achieve same performance, however, the TDMA scheme adapts to the optimal data rate much faster than the CTS/RTS scheme. In contrast, the CTS/RTS scheme performs poorly in substantial high link utilization scenario. It only achieves 3/4 of the data source rate and also generates jitter in data delivery. Our TDMA scheme outperforms the CTS/RTS scheme in both scenarios. More over the implementation of our scheme is not difficult and the communication overhead is low not requiring extra energy for sending negotiation packets such as CTS/RTS packets in the other scheme.

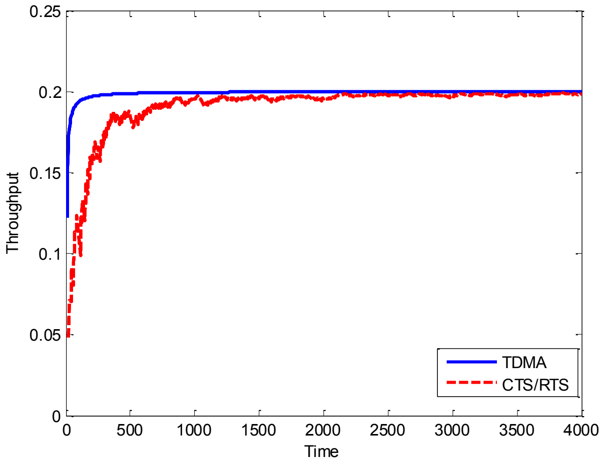

Figure 3. TDMA vs. CTS/RTS in Low Data Rate (Scenario 1)

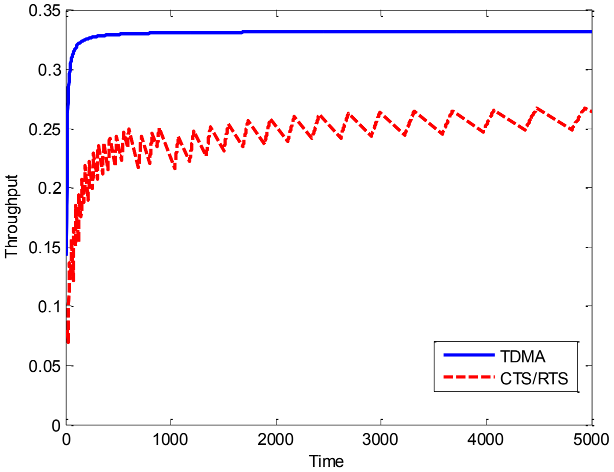

Figure 4. TDMA vs. CTS/RTS in High Data Rate (Scenario 2)

B. *Subsystem Throughput Estimation*

In order to show the accuracy of our estimation model, we conduct experiments to compare the subsystem throughput simulation results with our theoretical results. We assume the packet arrival interval of the subsystem is exponentially distributed with mean of 10 seconds, and the link transmission delay of a packet is one second. Consequently, the subsystem delay by applying our TDMA scheme is 3 seconds. By taking expectation on both sides of (2), we derive the theoretical expected throughput of the subsystem to be approximately 0.079 packets per second which is very close to the simulation result of 0.0784.

5. Conclusion and Future Work

In this paper, we propose a QoS-enabled dynamic path formation algorithm to yield throughput-aware video delivery based on a throughput estimation model. We suggest enhancing the performance of the video delivery over the WSN by isolating concurrent video streams to eliminate the path coupling interferences and efficiently distributing a limited number of mobile base stations to the block node location for each stream. Our mobile station deployment scheme not only improves the streaming egress of the network but also reduces the deployment cost for each stream by minimizing the distance between the mobile station and the primary gateway.

Although our proposed path formation algorithm achieves certain QoS by exploring the spatial diversity of the sensor network, it sacrifices the number of streams that a network can carry. In the future, a complimentary data transmission interference model should be considered for more complex video streaming applications. With the aid of this complimentary data path interference model, we will derive a more comprehensive mathematical throughput estimation expression that link the data path throughput to additional parameters, such as path relative positions, network size and number of concurrent data sending paths. These models will support the advanced path formation algorithm design for video streaming applications to fully explore the capacity of wireless sensor networks.

6. References

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