Application Aware Overlay One-to-Many Data Dissemination Protocol for High-Bandwidth Sensor Actuator Networks

Tarun Banka, Panho Lee, Anura P. Jayasumana, V. Chandrasekar
{tarunb, leepanho, anura, chandra}@engr.colostate.edu
Department of Electrical and Computer Engineering, Colorado State University,
Fort Collins, CO 80523

Abstract

An application-aware Deterministic Overlay One-to-Many (DOOM) protocol is proposed for meeting heterogeneous QoS requirements of multiple end users of High-Bandwidth Sensor Actuator Network (HB-SAN) applications. Although DOOM is initially targeted for use in collaborative adaptive systems of weather radars, it has been designed for use in wider class of sensing systems. DOOM protocol performs rate-based application aware congestion control by selecting end user specific subset of the sensor data for transmission thus adapting to available network infrastructure under dynamic network conditions. Performance of DOOM is evaluated for radar networking using a combination of Planetlab as well as an emulation based test-bed. It is shown that DOOM protocol is able to meet individual end user QoS requirements as well as aggregate QoS requirements of different end users. Moreover, multiple DOOM streams are friendly to each other as well as to TCP cross- traffic sharing the bottleneck link.

Keywords

Multicast, Congestion control, Overlay networks, Sensor networks, Transport protocol, Scheduler, QoS

1. Introduction

A new class of high-bandwidth sensor actuator networks (HB-SAN) is emerging that operates on the principles of collaborative and adaptive sensing of the environment. A sensor-actuator system is one where sensing is accompanied with the actuation of various devices, for controlling a phenomenon or the measurement process itself. In many of these systems, sensor generated data is transmitted to multiple end users. Different end users may have different real-time rate requirements and application level accuracy requirements. These requirements must be met concurrently over available network infrastructure and under dynamic network conditions for the proper operation of the HB-SAN application. Collaborative Adaptive Sensing of the Atmosphere (CASA) [11] is a prime example of such high bandwidth sensor actuator networks. As shown in Fig. 1, CASA is based on the concept of a network of small weather radars, integrated with a distributed processing and storage infrastructure in a closed loop system to monitor lower troposphere for atmospheric hazards like tornados, hailstorm etc. Video Surveillance and Live Virtual Reality are other upcoming high-bandwidth and computation intensive HB-SAN applications [9,15]. It is

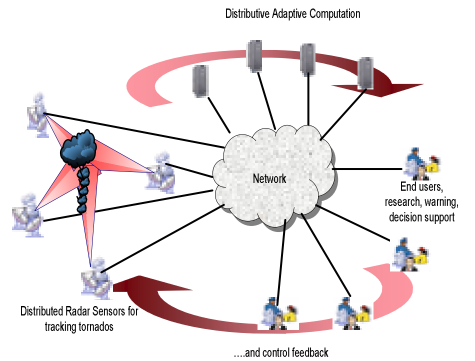

Figure 1. CASA high-bandwidth sensor actuator network

important to note that the term sensor networks has traditionally being used for networks of low-bandwidth sensor nodes with limited computation, memory and energy resources, operating in a broadcast wireless environment [1]. Alternatively, high-bandwidth sensor actuator networks like CASA and video surveillance may have different requirements and resource constraints. Note that we use the term sensor network and sensor actuator network interchangeably in this paper as our results are applicable to both. Most existing solutions for one-to-many dissemination of multimedia streaming are focused on properties and requirements of video streaming, which are significantly different from sensor data streaming [5,10,13]. There is a need for new application aware protocols that meets the requirements of sensor data streaming. The unhindered operation of many HB-SAN applications is critically important under catastrophic conditions, such as in the presence of tornados and hurricanes. Under such conditions, the underlying networking infrastructure may not be fully functional. Overlay network based implementations provide the flexibility to perform application specific tasks at overlay nodes such as alternate bandwidth rich path selection under failure conditions and application aware data drop at overlay nodes during network congestion [7,14,16]. Overlay network thus provide an attractive proposition for the deployment of application aware one-to-many data dissemination protocol. More information on the suitability of overlay networks for application aware one-to-many data dissemination is provided in [5].

We propose and evaluate an application aware **D**eterministic **O**verlay **O**ne-to-**M**any (DOOM) data dissemination protocol. DOOM is a sender driven high bandwidth, one-to-many data dissemination transport protocol with following key goals: (i) Given the rate determined by the congestion control algorithm, sub-sample and frame the data

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based on the data quality requirements of the end user, and (ii) Efficiently schedule different end user specific sub-sampled sets of high bandwidth data for transmission to multiple end users within bounded time.

Section 2 explains motivation for the application aware DOOM protocol. Section 3 explains DOOM protocol and implementation details. Performance results based on Plantlab and emulation based test-bed are presented in Section 4. Section 5 concludes the paper.

2. Motivation

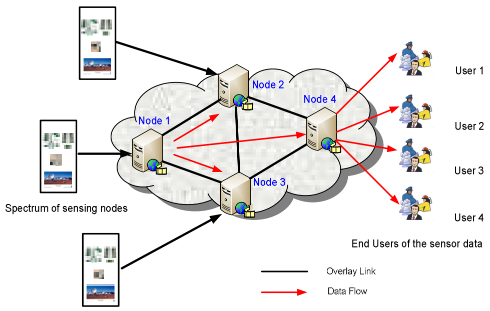


Figure 2. One-to-Many data dissemination scenario in high-bandwidth sensor actuator networks

Need for DOOM one-to-many protocol is felt due to distinct characteristics of HB-SAN as listed below:

(1) They are not resource constrained in terms of computation and energy when compared to traditional mote-based wireless sensor networks.

(2) Data generation rates can be in order of several Mbps to hundreds of Mbps per sensor node.

(3) Multiple end users/applications may be present that have distinct data rate requirements necessary for their real-time operation.

(4) End users/applications may have diverse data quality needs for acceptable accuracy in end results based on the specific use of the data, which must be satisfied concurrently for all users under dynamic network conditions and available network infrastructure. We use the term "end users" to refer to the entities such as end algorithms that use the sensor generated data for their operation.

(5) Characteristics of the sensor data can be significantly different from the video stream data, where data can be encoded in to different layers. Moreover, sensor data QoS requirements can significantly vary from one HB-SAN application to another or even from one sensor to another.

(6) HB-SAN in many of its incarnations may use end-to-end wired networks, wireless networks or mix of two for data transfer [4].

(7) Scalability requirements of HB-SAN are not as stringent when compared to large-scale distribution requirements of the video streams over the Internet. Multiple DOOM nodes, e.g., Node 1 and Node 4 in Fig. 2, may be deployed to serve different end users in different regions of the network.

End users have critical minimum rate requirements below which data is not useful. Depending on the available computation and network resources, end user also specifies the target rate above which data cannot be received by the user. End user applications have the best performance, i.e., minimum error in the end product, e.g., wind velocity estimate, when data is delivered from sensors to the receiver at the target rate. But under bandwidth-constrained scenarios, i.e., during network congestion when all the information cannot be transmitted to the end user in real-time, a subset of the information may be used to provide somewhat less accurate, yet acceptable end-product value. In many such applications, sensor data has a fixed format and a data generation rate. The application, however, may be able to determine a subset of the total data that can be transmitted at transmission rates lower than the generation rate of the sensing node, while preserving the accuracy of the end-product within acceptable tolerances. The subset of information to be transmitted is determined by knowing the characteristics of the sensor data and tolerance of end users to missing information. For example, in CASA, each radar node periodically generates digitized radar signal (DRS) blocks of data [5]. This fixed interval of a time is known as *heart-beat* of a sensor. Different radar algorithms show different levels of tolerance to the missing information in the DRS block, based on the intended use of the data, that can vary from user to user [6]. For example, some radar data end user algorithms such as reflectivity computation [6] can tolerate uniformly distributed random drops of information from a block of data generated by the radar sensor. Alternatively, an algorithm for Doppler velocity computation [6] can tolerate bursty drop of information. Similarly, other HB-SAN applications may show different levels of loss tolerance for certain types of information. It is this knowledge about the end user sensitivity to information loss that we propose to exploit in DOOM protocol while determining the most relevant information that should be transmitted at lower rates during network congestion.

3. DOOM: Deterministic Overlay One-to-Many Protocol

This section explains the sender-driven, time multiplexed, **D**eterministic **O**verlay **O**ne-to-**M**any (**DOOM**) protocol for high bandwidth data dissemination to multiple end users. While we develop the concept of DOOM based on radar applications, the protocol is general purpose for use in a broader class of HB-SANs where data has spatiotemporal dependencies [5,6].

Each end user contacts the DOOM server to initiate a radar data transfer session. End users independently specify their minimum rate (MR) and target rate (TR) requirements. Moreover, each user also specifies different data framing types corresponding to different data quality needs of the end users. DOOM uses an already existing congestion control protocol TRABOL [3] for rate adaptation. The key feature of the TRABOL is that during network congestion, it performs rate adaptation while considering end user specific minimum and target rate requirements. TRABOL adapts the transmission rate such that during congestion it does not fall below the required minimum rates. Similarly, when bandwidth is available, TRABOL increases rate to target rate.

DOOM uses a time multiplexed data scheduling scheme to select and encode data for transmission at rates determined by the TRABOL. Current implementation of DOOM supports two CASA specific data framing types, Type 1 and Type. In Type 1 data framing, it is ensured that during rate adaptation, data drops are distributed uniformly in a block generated by the radar sensor. Similarly for Type 2 data framing, data is dropped uniformly, but pairs of adjacent samples are transmitted in the same packet.

Data samples to be transmitted for a given transmission rate and framing type are determined at the initialization time and stored in the *data schedule tables* as shown in Fig. 3. End user specific rate and data framing requirements are stored in the *user list*. A *rate table* of supported transmission rates is defined starting with lowest rate to be supported for any user, Rate 1, to the maximum transmission rate to be supported, Rate n, as shown in Fig. 3. In the current implementation, Rate 1 is 1 Mbps and Rate n is 100Mbps. Number of rates supported in rate table is determined by the granularity requirement of the end user applications; in the current implementation, two adjacent rates in rate table differ by 1Mbps. As shown in Fig. 3, sample schedule tables store information about framing and subset of the samples to be transmitted for a given transmission rate. For supporting multiple data framing requirements, more than one data selection scheme is required, resulting in multiple entries corresponding to each supported rate in the *rate table*. Fig. 3 shows a case when DOOM protocol supports two different data framing requirements Type 1 and Type 2. For radar data applications, data schedule tables in Fig. 3 consist of samples that are selected for transmission out of a DRS block. DOOM performs deterministic data selection by run-time lookup in Spatial and temporal dependencies of data also influence how

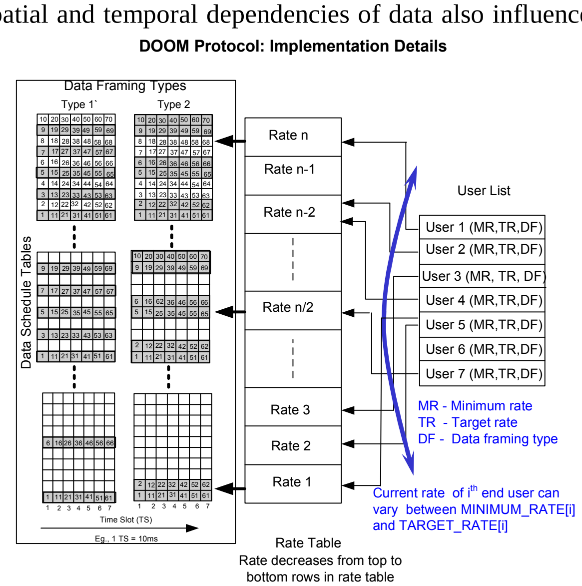


Figure 3. DOOM protocol implementation

```
DOOM Server
WHILE (1)
 { // Repeat following every heart-beat interval
  IF (USER_COUNT >0)
   { // Determine new transmission rate
     // of each client every heart-beat interval
    FOR (EACH USER IN user-list)
     { // Use TRABOL congestion control to
       // determine next transmission rate
      IF (ACK RECEIVED)
        {determine_TRABOL_rate(user, ACK) }
      else
        { determine_TRABOL_rate(user, NO_ACK) }
      // User next rate information is updated
      update_rate_table(user)
      }
    // Use Time multiplexing to transmit data
    FOR (EACH TIME SLOT )
     { FOR (EACH USER)
         { // Get data schedule table for the client
          data_schedule_table = get_reference(user)
          // Determine data to transmit for a given
          // client in the current time slot
          data = lookup(time_slot, data_schedule_table)
          send_data(data, user)
         } } } }
```

Figure 4. DOOM algorithm for one-to-many data dissemination

the appropriate *data schedule tables* for each scheduled end user based on its data framing requirement and current transmission rate. Note that with this approach it is possible for two end users to get different data even at the same transmission rate because of their different data framing needs. transmitted information is encoded for a particular end client. For example, depending on the observed event by a sensor, there may be a dependency between two adjacent samples of the generated data. In certain cases, one sample may not be useful without the other for the end applications. Thus it may be required to delivery adjacent samples, which can be achieved by sending both samples in the same packet. Fig. 3 shows data schedule tables corresponding to data framing requirement Type 2, where adjacent samples are transmitted in the same packet, are indicated by grey background.

As shown in Fig. 4 [5], TRABOL congestion control protocol determines the next transmission rate for each end user independently based on the packet loss count feedback received from the end user. A particular transmission rate is achieved by transmitting the data given in corresponding data schedule table within a *heart-beat* interval. Note that in case of DOOM, TRABOL always determines next transmission rate which is supported by the rate table in Fig. 3. In order to avoid sending all the data to a particular user in single burst and to support multiple data framing requirements, *heart-beat* interval is divided into multiple scheduling time slots of constant duration, e.g., 10ms time slot. Fig. 3 shows a case for 70ms *heart-beat* that results in 7 time slots of 10ms each. For time multiplexing, a periodic timer (e.g. 10ms) is used, and when this timer times out a table lookup is performed in the corresponding *data schedule table* for a particular end user to select the data for transmission. Data corresponding to current *time-slot* is then encoded and transmitted as per end user requirements. Note that in any one 10ms *time-slot* multiple end users can be scheduled to get data at different transmission rates. Time multiplexed data scheduling scheme enables concurrent transmission of different subset of data from the same DRS block to different end users in order to satisfy their unique rate and data framing requirements. Moreover excessive bursty-ness of data is avoided by scheduling the data for transmission uniformly over the *heart-beat* interval, i.e., over multiple *time-slots*.

Each end user sends back to the source the received packet count of data transmitted in the *heart-beat* interval. This helps in avoiding flood of ACK traffic from multiple end users to the DOOM server. At the start of periodic *heart-beat* interval, new transmission rates are computed for each end user using TRABOL, based on the last feedback from an individual user. After new transmission rates are determined for all the requesting end users, data can be transmitted using new data transmission schedules for that particular rate.

4. Performance Evaluation

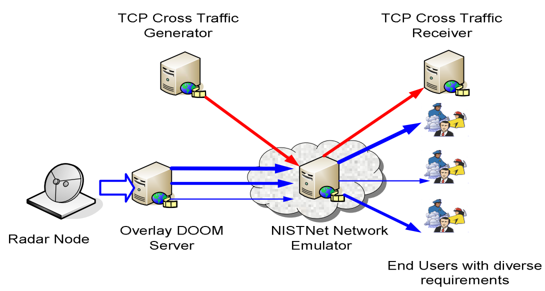


Figure 5. Network emulation test bed

Planet-Lab [12] and the emulation test-bed shown in Fig. 5 are used for the performance analysis of DOOM protocol. Latter is based on NISTNET [8] network emulator which emulates different network dynamics such as bandwidth and delay variations. We consider the case when a radar node generates data at a constant rate of 100Mbps. Experiments are performed to evaluate performance of DOOM overlay server in meeting different rate and data framing requirements of multiple end users simultaneously. Friendliness of DOOM streams to each other as well as TCP cross-traffic, sharing the bottleneck link is evaluated. Additional performance results can be found in [5].

Fig. 6 shows emulation test-bed based results for evaluating DOOM's effectiveness in meeting heterogeneous high bandwidth requirements of the different end users under varying bottleneck bandwidth conditions. Each of the end user has different TR and MR requirements as shown. In Fig. 6, when bottleneck bandwidth exceeds the sum of minimum bandwidth requirements of all end users, each user is able to meet its minimum rate requirement. When bottleneck bandwidth exceeds sum of target rate requirements of all end users, all the end users are able to receive data at their target rate requirements. Fig. 7 shows DOOM's effectiveness in meeting similar and different rate requirements of multiple end users based in different countries over Planetlab test-bed, served by DOOM overlay node in Colorado (USA). For most users, receiver throughput lies between their target and minimum rate. As shown in Fig. 7, the end user in Oregon (USA) receives data below its minimum rate because of either bandwidth or end node limitations. Fig. 8 shows results for quality of the received data over the Planetlab by multiple users with similar and different rate requirements. In case of CASA radar data streaming, quality of received data is measured by computing standard deviation in the reflectivity algorithm end results for each user. Lower standard deviation is a measure of better quality data. In Fig. 8, most end users in different countries of the world receive similar quality of the data using DOOM protocol at different receiver throughputs. Two end users, Oregon and Canada-1 show comparatively high standard deviation due to lower receiver throughput in case of Canada-1 node and due to random losses in the network for Oregon node because of bandwidth or end node limitations.

In HB-SAN, DOOM streams may share the network with already existing TCP traffic. Because of the high bandwidth requirements of different end users, TCP friendliness operation of the DOOM protocol is important. Fig. 9(a) shows the impact of multiple DOOM streams on the TCP cross traffic in the bottleneck bandwidth link. In this case, three end users with similar target rate requirement of 100Mbps, (referred as TR100) and different minimum rate requirement of 30Mbps, 50Mbps and 90Mbps (referred as MR30, MR50, and MR90) are considered. Bottleneck bandwidth is 250Mbps, which lies between sum of target rate requirements and sum of minimum rate requirements of all end users. As seen in Fig. 9(a), when there is no TCP cross traffic, all end users share the bottleneck bandwidth while satisfying their target rate and

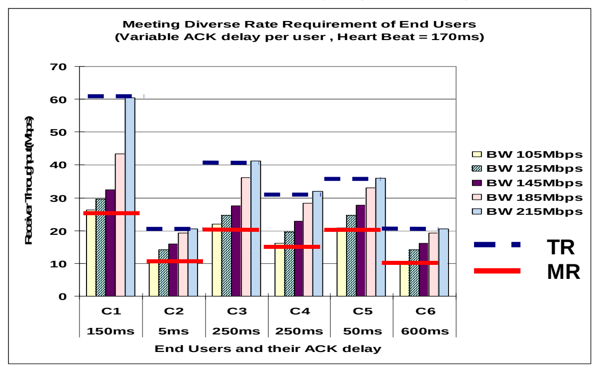


Figure 6. Performance of DOOM for meeting different rate requirements of multiple end users using emulation test-bed (data generation rate =100Mbps and heart-beat = 70ms)

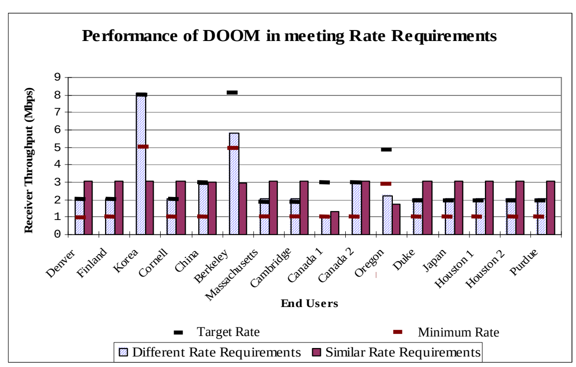


Figure 7. DOOM performance in meeting rate requirements of different end users with similar and different rate requirements (data generation rate = 10Mbps, heart-beat = 220ms). For similar rate requirement, TR = 3Mbps, MR=1Mbps

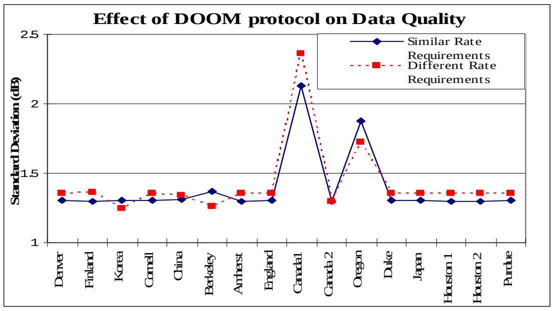
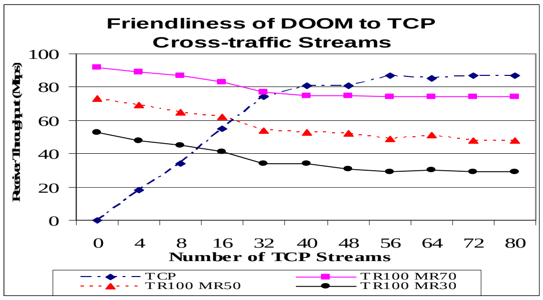
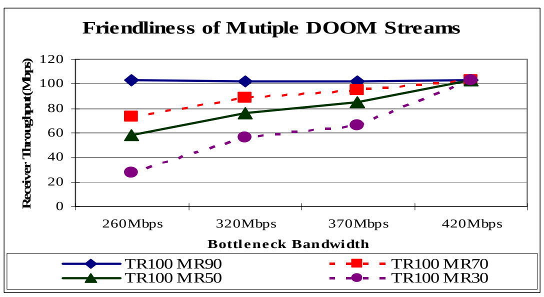


Figure 8. Effect of DOOM protocol on data quality for different end users with similar and different rate requirements



(a)



(b)

Figure 9. Friendliness of DOOM protocol (a) to TCP cross traffic streams (Bottleneck bandwidth = 250Mbps and RTT = 50ms) (b) to DOOM traffic streams sharing the same bottleneck link (RTT=10ms)

minimum rate requirements. As the number of TCP streams increases, receive throughput of all DOOM stream's sharing the link decrease and cumulative receive throughputs of TCP streams increases. Note that for each DOOM stream, throughput does not fall below the minimum rate requirements of individual end users.

In HB-SAN, it is possible that different DOOM streams share the same bottleneck link. Fig. 9(b) shows the emulation test-bed results for the DOOM streams friendliness to each other under varying bottleneck bandwidth conditions. Four end users with similar target rate and different minimum rate requirements are considered. Bottleneck bandwidth varies between 260Mbps and 420Mbps. When bottleneck bandwidth is 260Mbps, three users receive data at or above their minimum rate except the user with target rate of 100Mbps and minimum rate of 90Mbps, which is always receiving data at its target rate. As the bottleneck bandwidth increase, receive rate for the end users starts increasing. Note that throughput of all end users equally share any extra available bandwidth till the target rates of end users are achieved.

5. Conclusions

The application aware DOOM protocol is proposed for one-to-many high bandwidth data dissemination for sensor actuator network applications. Its effectiveness in meeting both rate and data quality requirements is demonstrated using Planetlab and an emulation based test-bed. Emergence of CASA like sensor actuator applications has the potential to hasten the arrival of many more such applications. Overlay networks could provide an effective medium for the deployment of such application aware data dissemination protocols and transport services for sensor actuator networks. Future work includes the scalability analysis of DOOM protocol by using multiple DOOM servers in the overlay network.

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