1-2010

Towards Context-Aware Real-Time Information Dissemination

Kyoung-Don Kang
Binghamton University--SUNY, kang@binghamton.edu

Greg Vert

Towards Context-Aware Real-Time Information Dissemination

Kyoung-Don Kang
Department of Computer Science
State University of New York at Binghamton
kang@cs.binghamton.edu

Greg Vert
Department of Computer Information Systems
Texas A&M University, Central Texas
gvert@cse.unr.edu

Abstract

Real-time information dissemination is essential for the success of key applications such as transportation management and battlefield monitoring. In these applications, relevant information should be disseminated to interested users in a timely fashion. However, it is challenging to support timely information dissemination due to the limited and even time-varying network bandwidth. Thus, a naive approach disseminating every data with no consideration of the context that describes where and when the data is acquired and how it can satisfy users may only provide poor performance and user perceived quality of service (QoS). To address the problem, we design a novel context-aware protocol to disseminate real-time data in a cost-effective manner by considering the spatio-temporal semantics associated with information. More specifically, we define (1) context attributes, (2) develop how to analyze the utility of a specific data item based on the attributes, (3) and adjust the utility based on a cost-benefit analysis for cost-effective real-time information dissemination especially in the context of visual surveillance.

1 Introduction

Real-time information dissemination is needed in a number of important applications such as transportation management, target tracking, and battlefield monitoring. Unfortunately, computational resources, especially the network bandwidth, for information dissemination is limited. Also, the available bandwidth may significantly vary from time to time, especially when information is disseminated via wireless communication media. Hence, a naive approach disseminating every data with no consideration of the *context* that describes where and when the data is acquired and how it can satisfy users may only provide poor performance and user perceived quality of service (QoS).

To shed light on the problem, we design a new approach to *context-aware real-time information dissemination* in publish-subscribe systems. Essentially, we aim to utilize the limited bandwidth in a cost-effective manner to improve the user perceived QoS by considering the context inherent in real-time sensor data characterized by the spatial and temporal semantics of the data and user interests, and cost for updating and disseminating data. In this paper, we focus on airborne surveillance and tracking scenarios using unmanned aerial vehicles (UAVs), even though our approach is not limited to a specific application. For example, UAVs can collect images and forward them to nearby command and control (C2) nodes or ground forces to support visual target tracking or reconnaissance as shown in Figure 1.

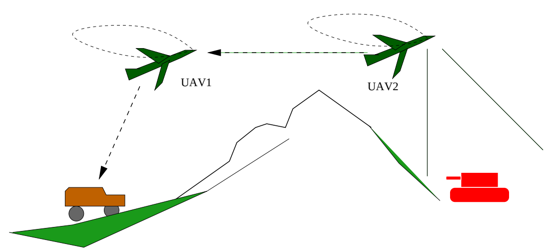


Figure 1. Information Dissemination for Surveillance

Generally, the bandwidth for airborne communications is limited. Link 16 is commonly used for tactical communications between military aircraft, but it only supports $28.8 - 238$ Kbps [10]. Also, the available wireless bandwidth may substantially vary during a mission, as the terrain, weather, and communication distance changes [5]. Hence, context-aware real-time information dissemination is critical to provide the right information to the right users at the right time [17, 4] in defense information systems such as the US Air Force Joint Battlespace Infoshpere (JBI) despite the challenges. In order to provide adequate QoS to intelligence, surveillance, and reconnaissance applications in net-centric environments, it is critical to ensure that information publishers, such as UAVs, disseminate the most important information first to the subscribers, such as the other aircraft or ground forces, in a timely manner despite varying network conditions [1]. Also, it is important to efficiently utilize the highly constrained and potentially varying available wireless bandwidth.

In the JBI, a managed information object (MIO) is the quantum over which information dissemination is managed. An MIO consists of the data to be delivered and the metadata that describes the data. For efficient dissemination of MIOs, we consider the *spatio-temporal features* of MIOs including the MIOs' acquisition times and coverage of the area of interest (AOI), which partly determine the information utility perceived by users. In this paper, each information object is associated with the spatial and temporal metadata as well as the estimated utility in addition to the data itself.

In this paper, we first define several context attributes needed to compute the estimated utility of MIO dissemination. Estimating the information gains (i.e., utilities) provided by MIOs based on multiple context attributes and comparing them with each other is a non-trivial problem [11]. To address the challenge, we develop a compact set of contextual QoS attributes and an efficient method to estimate information utilities. Also, we develop a scheduling algorithm to increase the total utility as much as possible, while efficiently utilizing the limited and potentially fluctuating available network bandwidth by carefully scheduling the dissemination of MIOs.

Deriving proper end-to-end (E2E) deadlines for airborne information dissemination and meeting all E2E deadlines is very difficult, if at all possible, due to a number of challenges including fluctuating channel conditions and different importance and size of data objects. Therefore, we focus on supporting *soft real-time* MIO dissemination by striving to improve the contextual QoS and reduce the E2E delay as much as possible. In this paper, we apply the *delay tolerant networking* (DTN) technique [3], as the continuous E2E connectivity is not always available in airborne networks [7]. DTN is a store-and-forward approach that does not require an E2E connectivity. In this paper, if an airborne information dissemination node receives a packet from its one-hop neighbor, it immediately acknowledges the reception and stores the received packet before it forwards the packet to the next node, for example, in a group of UAVs or ground forces inter-connected for surveillance.

The rest of the paper is organized as follows. Section 2 formulates the problem of context-aware real-time information dissemination. Our cost-benefit analysis and approach to context-aware real-time data dissemination is discussed in Section 3. Related work is discussed in Section 4. Finally, Section 5 concludes the paper and discusses future work.

2 Problem Formulation

We model the contextual QoS optimization problem as a linear programming model. For the clarity of presentation, we consider a simple case where one UAV has $n(\geq 1)$ MIOs to disseminate. We assume that the utility u_i achieved by an instance of MIO_i, e.g., an image taken from a specific geographic area, is known for problem formulation purposes. By assigning transmission rates, $f_1, f_2, ..., f_n$ to MIOs, our approach to MIO dissemination aims to maximize the total utility

$$\sum_{i=1}^{n} u_i f_i \tag{1}$$

subject to

$$\sum_{i=1}^{n} f_i \leq f \tag{2}$$

where f is the wireless bit rate bound. However, mapping the problem of context-aware MIO dissemination as a linear programming problem has pitfalls including the following ones:

- For example, The utility of an MIO is not fixed but may change based on the context that represents potentially varying user interests in MIOs. Spatio-temporal contexts may change the importance or utility of an MIO. For example, the utility of an image from a certain UAV reduces, if another UAV covers the AOI better. Thus, u_i in Eq 1 is not fixed but may vary from time to time.

- The available wireless bit rate is not constant but varies oftentimes. Hence, f in Eq 2 changes. Thus, we observe that our problem is a significant departure from utility maximization based on linear programming and, therefore, investigate cost-effective heuristics for real-time information dissemination.

3 Real-Time Information Dissemination

In this section, we describe the contextual QoS attributes and scheduling algorithm to support adaptive, context-aware MIO dissemination. Using the context attributes, the utility of each MIO is computed. Based on the estimated utility values, MIOs are disseminated in a highest utility first manner. Further, the MIO dissemination rate is dynamically adapted according to the available wireless bandwidth estimated based on the measurements performed in the recent history.

3.1 Overall Approach to Scheduling of Information Dissemination

In our approach, each publisher, e.g., each UAV, works as either the information source or relay node toward the destination. Each node has a buffer to store its own data or the data received from the other nodes. Given multiple information objects to deliver, each node computes the estimated utilities of the MIOs to be disseminated. It also performs the cost-benefit analysis to adjust the MIO utilities and schedule their dissemination to increase the total utility perceived by the subscribed users. Further, the bit rate bound for MIO dissemination is continuously adjusted via feedback to improve the accuracy of the available bit rate estimation. The overall procedure is summarized in Figure 2. Also, the individual steps described in Figure 2 are discussed in the next subsections.

3.2 Context Attributes

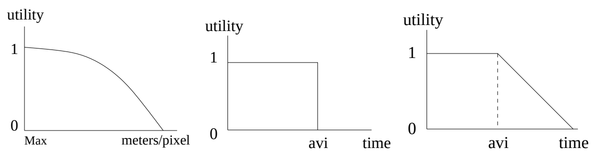
To estimate the utility of an information object, it is necessary to consider the context in which the information is acquired and used. Also, the context for real-time data acquisition and dissemination is often determined by several attributes. In this section, context attributes for real-time information dissemination are defined based on the notion of the spatio-temporal gain. Since disseminating two information objects with the same contextual utility may require and result in different amounts and levels of computational resources and user satisfactions, it is desired to analyze the cost for disseminating individual MIOs and adjust their utilities accordingly.

1. For each MIO to disseminate, compute the estimated spatio-temporal information gain, i.e., the utility, the MIO is expected to produce.

2. For the MIO, compute its cost-benefit ratio and adjust the spatio-temporal gain by the cost-benefit ratio. Insert the MIO into the queue of the MIOs to be disseminated in non-increasing order of the utility. If the queue is full, delete the MIO with the smallest utility first.

3. At the beginning of a dissemination period, transmit the MIO at the head of the queue and wait for an acknowledgement (ACK) from the receiver. After receiving the ACK, transmit the next MIO. In this way, transmit as many MIOs in the queue as possible until the end of the current dissemination period. At the end of the period, go to Step 1.

Figure 2. Adaptive, Context-Aware QoS Support for Real-Time Information Dissemination



(a) Image resolution (b) Validity interval (c) Soft freshness metric

Figure 3. Spatio-Temporal Utility of an MIO

3.3 Utility Estimation

In this paper, we consider the spatial and temporal aspects associated with an MIO to estimate its utility. Clearly, these attributes are not only possible metrics that can analyze the utility of an MIO. However, the spatial and temporal aspects of sensor data are critical in terms of real-time information dissemination, because they indicate how closely the MIO captures the AOI and the current real world status.

- *Spatial gain:* Figure 3(a) shows an exemplar utility function based on the resolution of an image covering the AOI expressed in terms of meters per pixel. The utility is 1 if an MIO has the maximum resolution determined by the camera hardware and the lowest possible altitude that does not risk the safety of the UAV. The utility decreases as the resolution decreases, i.e., as the meters/pixel increases, as shown in the figure.

- *Information freshness:* Generally, an MIO is more valuable, if it is acquired more recently. According to the temporal validity concept developed for real-time data management [12, 8], MIO_i is fresh (i.e., temporally consistent) at time t, if $t \leq ts(MIO_i) + avi(MIO_i)$ where $ts(MIO_i)$ is the time-stamp taken when MIO_i is acquired and $avi(MIO_i)$ is the absolute validity interval of MIO_i determined by the semantics of a specific application. As shown in Figure 3(b), the MIO is considered stale producing no utility when t becomes larger than $ts(MIO_i) + avi(MIO_i)$.

Unfortunately, the absolute validity interval metric is too rigid for real-time information dissemination in a distributed environment. Thus, we propose an alternative metric, called a *soft freshness metric*, to measure the freshness of MIO_i in a more flexible manner. As shown in Figure 3(c), the freshness, i.e., temporal utility, of MIO_i gradually decreases to 0 as t increases beyond $ts(MIO_i) + avi(MIO_i)$. In practice, a precise shape of the freshness curve is application dependent; it can be defined by an application administrator using the application program interface (API). Notably, most existing work on real-time data management only considers data temporal consistency in terms of validity intervals without considering soft freshness or spatial aspects [12, 8].

To compare the estimated utilities of MIOs, we compute the *spatio-temporal gain* of MIO_i as a weighted sum of the utility values acquired by the resolution and freshness.

$$\omega(MIO_i) = w_s \cdot u_s(MIO_i) + w_t \cdot u_t(MIO_i) \qquad (3)$$

where w_s, $u_s(MIO_i)$, w_t, and $u_t(MIO_i)$ represent the weight for the spatial utility, spatial utility value of MIO_i, weight for the temporal utility, and temporal utility value of MIO_i, respectively. Tuning w_s and w_t is specific to the application of interest. Also, it needs to satisfy the following constraint:

$$w_s + w_t = 1 \qquad (4)$$

Therefore, $\omega(MIO_i) \in [0, 1]$ in Eq 3.

The default setting is $w_s = w_t = 0.5$ to consider temporal and spatial gains equally. There are a number of ways to determine w_s and w_t including the following ones:

- An application administrator can tune w_s and w_t to weigh the spatial and temporal utilities in a specific application based on his/her expert domain knowledge to compute the utility via Eq 3, while meeting the constraint specified in Eq 4. The administrator can also specify a set of (w_s, w_t) pairs to allow the information dissemination system to use different pairs considering the current tactical situation. For example, it is reasonable to increase w_s (and decrease w_t) for long-term planning of possible missions in a distant AOI. Alternatively, it could be more desirable to increase w_t (and decrease w_s) to detect immediate threats over the next hill.

- Alternatively, our approach allows each individual user to choose w_s and w_t. This approach is also reasonable as individual users may have different preferences between the spatial coverage and information freshness. When an individual user subscribes to our information dissemination service, he/she specifies the preference by setting w_s and w_t subject to the constraint of Eq 4. In this case, the same MIO can be perceived with different utility values by different users. For each MIO, we compute the total utility, which is equal to the sum of the utilities preceived by the users. After that, we compare the total utilities of MIOs to schedule MIO dissemination.

The choice between the first and second approach is highly dependent on the specific application of interest and current situation. For example, the first approach is expected to be more effective, if the AOI is already determined and specific targets are identified. On the other hand, the second approach is more effective when different users want to analyze complex battlefield situations from different perspectives and derive synergistic intelligence that could be missed otherwise. Thus, we provide both options in this paper.

3.4 Cost-Benefit Analysis and Utility Adjustment

In a publish-subscribe system, not every client may subscribe to a certain MIO. Instead, some MIOs could be more or less popular depending on tactical situations and user interests. Further, their update frequencies may vary widely. Essentially, it is desired to disseminate the MIO that is the most popular, least frequently updated, and smallest in terms of size first. Based on this observation, we compute the *cost-benefit ratio*, $\beta(MIO_i) \in (0, 1)$, for arbitrary MIO_i using a sigmoid function:

$$\beta(MIO_i) = \frac{1}{1 + \sigma} \qquad (5)$$

where

$$\sigma = e^{-af(MIO_i)+uf(MIO_i)+s(MIO_i)+d(MIO_i)^{\alpha}} \quad (6)$$

and $af(MIO_i)$ is the access frequency of MIO_i, $uf(MIO_i)$ is the update frequency of MIO_i, and $s(MIO_i)$ is the size of MIO_i normalized to the average MIO size. Also, $d(MIO_i)$ in Eq 6 is the distance between the sender and receiver normalized to the average distance. Because the signal to noise ratio (SNR) exponentially decreases in terms of distance between the sender and receiver [9], it becomes more expensive to transmit MIO_i as the distance increases. Typically, α in Eq 5 is greater than or equal to 2 and changes according to the surrounding environment [9]. To compute $\beta(MIO_i)$, we propose to use a fixed α value, because the cost-benefit ratios are mainly used to determine the relative rankings of MIOs.

Finally, we adjust the spatio-temporal gain computed in Eq 3 by the cost-benefit ratio to compute the adjusted utility of MIO_i, $G(MIO_i)$, which is in the range (0,1):

$$G(MIO_i) = \beta(MIO_i) \cdot \omega(MIO_i) \quad (7)$$

Overall, the adjusted spatio-temporal utility increase as MIO_i becomes more popular, but it decrease if MIO_i is relatively large, updated more frequently, or transmitted to more distant users.

In this paper, we consider periodic information dissemination. Each UAV periodically disseminates its information at every dissemination period. It disseminates the data with the highest adjusted utility first. If it cannot finish disseminating all the data within the period, it recomputes the utilities of the remaining and newly acquired data, if any, for data dissemination in the next period. To support DTN using a finite buffer, the data with the smallest utility is deleted when the storage in a UAV is full. In this way, we aim to enhance the user perceived QoS as much as possible in the presence of the potentially time-varying availability of the wireless bandwidth and storage capacity.

4 Related Work

A goal of research on the application of context has been to have computational process affected by the environment it exists in. For example, a cell phone should sense that its owner is in a meeting and forward incoming calls to voice mail as a result. Schilit [13, 14] was one of the first researchers to coin the term context-awareness. Dey [6] extended the notion of a context with that of the idea that information could be used to characterize a situation and thus could be responded to. Recently, more powerful models for contextual processing have been developed in which users are more involved. However, related work on context-aware real-time information is scarce.

Data broadcasting over a wireless link, such as a satellite link, has been studied [16, 15, 18]. A majority of existing work on data broadcasting is centralized where the server has all data to disseminate and schedules data broadcast to minimize the latency. However, in real-time information dissemination systems, there can be more than one information sources. Aksoy et al. [2] has considered the multiple source problem in the context of data broadcast. Most of existing work on data broadcast, however, does not apply the notion of context to support cost-effective data dissemination in the presence of intermittent wireless connectivity.

Our work is novel in that it develops and seamlessly integrates spatio-temporal context attributes and cost-benefit analysis for real-time information dissemination. Context-aware real-time information dissemination is critical to provide the right information to the right users at the right time [17, 4] in defense information systems. Further, it is essential for other important applications such as disaster recovery or traffic status monitoring. However, the related work is scarce. The closest work is real-time data broadcast [16, 15, 18, 2]; however, most existing work on data broadcast do not directly consider the notion of context. Further, they are not integrated with delay tolerant networking to make data available even in the presence of the intermittent wireless connectivity.

5 Conclusions and Future Work

Real-time information dissemination is needed in a number of important applications such as transportation management, target tracking, and battlefield monitoring. However, it is challenging to support real-time information dissemination as computational resources are limited and their availability may dynamically vary. Hence, a naive approach disseminating every data with no consideration of the *context* that describes where and when the data is acquired and how it can satisfy users may only provide poor performance and user perceived QoS. To shed light on the problem, we design a new approach to *context-aware real-time information dissemination*. We aim to utilize the limited and potentially fluctuating communication bandwidth in a cost-effective manner to improve the user perceived QoS by considering the context inherent in real-time sensor data characterized by the spatial and temporal semantics of the data, user interests, and cost for updating and disseminating data. In this paper, we especially focus on airborne surveillance and tracking scenarios. The key contributions of this paper are as follows:

- We have defined context attributes for real-time information dissemination.
- We have developed how to analyze the utility of a specific data item based on the attributes and adjust the utility based on a cost-benefit analysis for cost-effective real-time information dissemination.
- In addition, a new scheduling scheme for cost-effective real-time data dissemination and buffering for delay tolerant networking has been developed.

In the future, we will develop more efficient approaches to context-aware real-time information dissemination.

Acknowledgments

This work was partly supported by the Visiting Faculty Research Program provided by the Air Force Research Laboratory (AFRL), Rome, New York in 2009. We appreciate Dr. Mark Linderman and other researchers at AFRL for their invaluable insights and discussions regarding this work. We also appreciate anonymous reviewers.

References

[1] C. Adams. Network Centric, Rush to Connect. Available at `http://integrator.hanscom.af.mil/2005/June/06162005/06162005-06.htm`.

[2] D. Aksoy, M. Franklin, and S. Zdonik. Data Staging for On-Demand Broadcast. In *International Conference on Very Large Data Bases*, 2001.

[3] V. Cerf, S. Burleigh, A. Hooke, L. Torgeson, S. Durst, K. Scott, K. Fall, and H. Weiss. Delay Tolerant Networking Architecture, April 2007. IETF RFC 4838.

[4] V. T. Combs, R. G. Hillman, M. T. Muccio, and R. W. McKeel. Joint Battlespace Infosphere: Information Management within a C2 Enterprise. In *International Command and Control Research and Technology Symposium*, 2005.

[5] D. Corman. WSOA–Weapon Systems Open Architecture Demonstration–Using Emerging Open System Architecture Standards to Enable Innovative Techniques for Time Critical (TCT) Prosecution. In *IEEE/AIAA Digital Avionics Systems Conference*, 2001.

[6] A. K. Dey. Understanding and Using Context. *Personal Ubiquitous Computing*, 5(1):4–7, 2001.

[7] T. Jonson, J. Pezeshki, V. Chao, K. Smith, and J. Fazio. Application of Delay Tolerant Networking (DTN) in Airborne Networks. In *IEEE Military Communications Conference (MILCOM)*, 2008.

[8] K. Y. Lam and T. W. Kuo, editors. *Real-Time Database Systems*. Kluwer Academic Publishers, 2006.

[9] B. G. Lee, D. Park, and H. Seo. *Wireless Communications Resource Management*. Wiley, 2009.

[10] JTIDS: Joint Tactical Information Distribution System. Available at `http://www.rockwellcollins.com/ecat/gs/JTIDS.html`.

[11] J. P. Loyall. Context Aware QoS Study. Technical Report SPO900-98-D-4000, Air Force Research Laboratory Information Directorate and BBN Technologies, March 2009.

[12] K. Ramamritham, S. H. Son, and L. DiPippo. Real-Time Databases and Data Services. *Real-Time Systems*, 28(2-3):179–215, Nov.-Dec. 2004.

[13] B. N. Schilit, N. Adams, and R. Want. Context-Aware Process Design: Exploring the Extrinsic Drivers for Process Flexibility. In *Workshop on Mobile Computing Systems and Applications*, 1994.

[14] B. N. Schilit and M. M. Theimer. Disseminating Active Map Information to Mobile Hosts. *IEEE Network*, 8(5):22–32, 1994.

[15] Mohamed A. Sharaf and Panos K. Chrysanthis. On-Demand Broadcast: New Challenges and Scheduling Algorithms. In *MobiCom*, 1998.

[16] C. J. Su and L. Tassiulas. Broadcast Scheduling for Information Dissemination. In *INFOCOM*, 1997.

[17] C. N. Sweet and S. Kanefsky. The C2 Constellation: A US Air Force Network Centric Warfare Program. In *International Command and Control Research and Technology Symposium*, 2004.

[18] J. Xu, X. Tang, and W. C. Lee. Time-Critical On-Demand Data Broadcast: Algorithms, Analysis and Performance Evaluation. *IEEE Transactions on Parallel and Distributed Systems*, 17(1):3–14, 2006.