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C. ESPOSITO[1,2], D. COTRONEO[1,2] , S. RUSSO[1,2]

[1] ***University of Napoli Federico II, Italy***
[2] ***Consorzio Interuniversitario Nazionale per l'Informatica (CINI), Lab. "C. Savy", Italy***

DATA DISTRIBUTION FOR MISSION CRITICAL SOFTWARE SYSTEMS

Several innovative industrial projects are developing novel complex distributed mission-critical systems consisting of Internet-scale federations of heterogeneous entities via middleware solutions. The middleware architectures that are currently adopted in this context are based on the publish/subscribe interaction model, which owns intrinsic decoupling properties and implicit multicast capabilities. Such novel critical systems require the adopted publish/subscribe middleware to jointly support several non-functional requirements, such as reliability, timeliness, scalability and flexibility by offering proper Quality-of-Service policies. However, current middleware products exhibit several limitations in supporting multiple non-functional requirements. This paper describes in details such limitations, and presents a series of candidate solutions to overcome them.

Key words: *Large-scale Complex Critical Infrastructures, Publish/subscribe middleware, Reliability, Timeliness.*

Introduction

Complex distributed mission-critical systems, adopted in application domains such as air traffic control and homeland security, are evolving from the traditional vision of "closed world" systems, to novel federated architectures, often named *Large-scale Complex Critical Infrastructures* (LCCI) [1].

In these systems, standard data dissemination technologies play a key role, and among them *Distributed Event-Based Systems* (DEBS), using the publish/subscribe paradigm [2]. Indeed, DEBS feature asynchronous multi-point communication, with intrinsic decoupling properties that enforce scalability and flexibility. For these reasons, they are felt as a proper technology for LCCI. LCCI typically impose on the adopted middleware platform the satisfaction of several non-functional requirements, including reliability, timeliness, scalability and flexibility. Satisfying all of them at the same time is a challenging issue for DEBS. Commercial solutions exhibit several limitations, where the satisfaction of some of these requirements is preferred at the expenses of other ones.

This paper first discusses open issues in publish-subscribe data distribution middleware for LCCI. Then it presents some proposals to address them, along with experiment results. The following approaches are investigated: *i)* the use of peer-to-peer techniques in federated middleware architectures to improve scalability of event dissemination and to allow adaptive solutions for the reliability concerns of LCCI; *ii)* the adoption of spatial redundancy by means of Forward Error Correction (FEC) techniques to balance reliability and timeliness for communications over wide-area networks; and *iii)* the evaluation of tree-based serialization formats and loss-less compression techniques to improve flexibility without affecting timeliness to a severe extent.

Motivating Example

Several on-going long-term industrial projects aim to develop LCCI in the form of Internet-scale federations of autonomous and heterogeneous systems that interoperate to provide critical facilities. This represents a novel perspective on how next generation mission-critical systems are architected: a shift in scale and in the structure, from monolithic and vertical architectures, which characterized traditional systems, toward large, highly modular and integrated systems.

A concrete example is the road map outlined by EUROCONTROL for the European Air Traffic Control (ATC) evolution, object of the European Research Project "*Single European Sky ATM Research*" (SESAR). The current European ATC framework is segmented among several systems (*Area Control Centers*, ACC), each responsible for a well-defined portion of the air space [3]. In order to handle the growing aviation traffic, the proposed solution is a framework where the ATC operations are seamless and fully integrated. To this aim, the novel ATC framework will be based on a data-centric model in which all ACC cooperate via a data distribution service [4][1].

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[1] This is one of the themes of the private-public laboratory *Iniziativa Software* (www.iniziativasoftware.it) between CINI / University of Napoli and SELEX, a Finmeccanica company which develops mission critical systems for ATC and homeland security.

Problem Statement

Recently, *Distributed Event-Based Systems* (DEBS) [5] are facing an increasing success for federating heterogeneous systems and for data dissemination at large scale. In such middleware solutions, information is denoted as *event*, and the act of delivering information related to an event is indicated as *notification* or *event dissemination*. Communication activities in such middleware have been formalized in the Publish/Subscribe model [2]: applications called *publishers* disseminate events through a *notification service* to interested applications, namely *subscribers*. The decoupling of production and consumption of notifications that is provided by all publish/subscribe services has been proved to enforce scalability since all explicit dependencies between publishers and subscribers are removed. Due to the offered decoupling properties, publish/subscribe services allow guaranteeing a scalable information distribution even in case of Internet-scale systems.

Their intrinsic features make DEBS a suitable solution for the design of LCCI. In fact, EUROCONTROL has decided that the technology to be used in the project SESAR is the recent OMG standard for publish/subscribe middleware called *Data Distribution Service* (DDS) [6]. However, to be successfully adopted to devise an LCCI, such middleware products need to provide means to jointly assure timeliness, reliability, scalability and timeliness:

– *Reliability and Scalability*: LCCI are devised by interconnecting different networks, so they can be regarded as systems of systems. This strong heterogeneity implies that network conditions are not the same all over the system; so, as for reliability strategies in DEBS, one solution does not fit all. The middleware has to be adaptive by using the proper strategy depending on many factors, including network condition, in terms of loss probability and burst length.

– *Reliability and Timeliness*: current publish/ subscribe platforms fail to provide reliable and timely event dissemination. In fact, the reliability gain is always obtained at the cost of predictability of performance;

– *Flexibility and Timeliness*: for performance reasons, most of the middleware products, including DEBS, adopt serialization formats that couple the comprehension of received messages to the knowledge of the structure of sent messages. This limits the flexibility offered by the communication infrastructure.

Reliability vs. Scalability

The topology of the current Internet is composed of interconnected *Routing Domains*, each one sharing common administration control and routing protocols [16]. Domains exhibit a hierarchical topological organization characterized by two abstraction levels, as illustrated in the lower part of Fig. 1. On one hand, there are the so-called *Stub Domains* within which the path joining two of its nodes resides. These domains may consist of Local Area Networks (LANs) or Autonomous Systems (AS), and are managed by a central organization. So, policies to assure Quality-of-Service (QoS) constraints in the data dissemination may be applied. On the other hand, *Transit Domains* are in charge of efficiently interconnecting several stub domains and to form the network backbone. Due to a lack of a central management reference and traffic orchestrator, transit domains are affected by several failures that may compromise the effectiveness and resiliency of the message forwarding. Although important technical progress [17] has been made to address this issue, more work needs to be done to achieve trustworthy QoS guarantees in Internet.

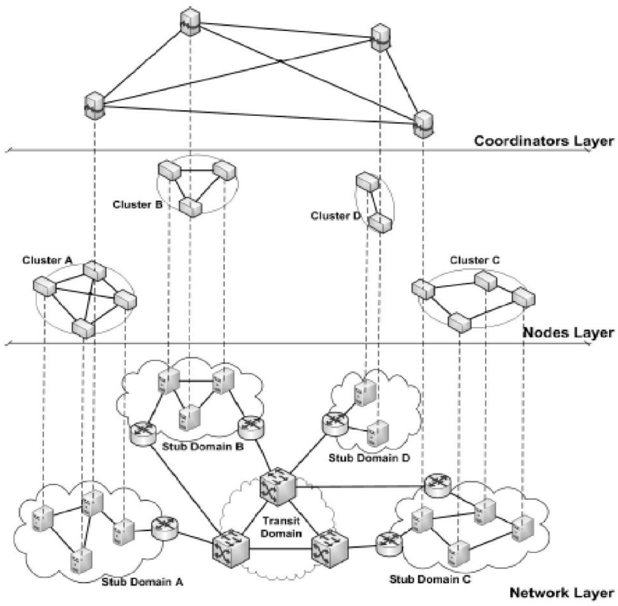

Figure 1. Different layers of abstraction in a publish/subscribe service

As shown in the upper part of Figure 1, we propose a hierarchical approach to organize a publish/subscribe service, which reflects the previous considerations on the Internet topology: 1) for simplicity a node runs only a single process, 2) nodes in the same domain are clustered together, and 3) each cluster holds a coordinator that allows interactions with the other clusters. Nodes in the same cluster communicate using *intra-cluster routing*, and can send messages outside the cluster only through their coordinator. In fact, a coordinator allows communications to the outside world exchanging messages with other coordinators using an *inter-cluster routing*. Since Internet comprises multiple domains with dissimilar QoS, intra-cluster and inter-cluster routing can be designed separately so to choose the right reliability strategy depending on the experienced network conditions.

Reliability vs. Timeliness

The focus of the publish/subscribe community has seldom been on reliable event dissemination for two main reasons. On one hand, guaranteeing message delivery despite network failures has been always thought as being inherited by the publish/subscribe system from the protocol used to implement the notification service. On the other hand, there were more challenging issues to be addressed first, such as scalability and expressiveness. However, the research interest of the community is recently shifting toward novel approaches to satisfy reliability requirements including new techniques developed specifically for these middleware to cope with several kinds of faults [7 – 9]. However, these efforts lack an adequate support to assure reliability along with timeliness.

In [10], we have noticed that mostly all the available publish/subscribe solutions adopt temporal redundancy to tolerate message losses, i.e., when a message loss is detected by a given subscriber, a retransmission is triggered on the publisher side. However, retransmission-based schemes obtain reliability at the expenses timeliness predictability. In fact, the delivery latency is strongly affected by the number of retransmissions needed to distribute a message tolerating failures. Since message deliveries over wide-area networks exhibit not-negligible bursty loss patterns [11], and studies have proved that network behavior is not constant during the day [12], the number of needed retransmissions can be considerable and hard to estimate beforehand. Therefore, latency is unpredictable and characterized by severe performance fluctuations, so the publish/subscribe service is unable to provide timeliness guarantees.

A practical solution to provide jointly reliability and timeliness is adopting spatial rather than temporal redundancy. Specifically, the publisher forwards additional information along the content of the event to be disseminated, so that when a loss occurs subscribers have a mean to obtain the original messages without requiring any retransmissions. Two approaches to spatial redundancy are: *Forward Error Correction* (FEC) [13] and *Multiple Trees* [18].

Considering that several prior studies have demonstrated that current Internet exhibits redundant connections at AS-level [19], network failures can be handled by exploiting path redundancy. This is the key idea underlying Multiple Trees, which consist of creating several overlapping trees so to reduce delivery ratio and to better cope with stringent real-time deadlines [20]. However, Multiple Trees approach enforces reliability and timeliness under the strict condition to guarantee diversity among the paths composing the Multiple Trees. If path diversity is not satisfied, failures of a networking device or link can jointly affect several, or all, redundant paths. In [10], we have proposed a novel joining procedure for tree-based publish/subscribe so to build a forest of disjoint trees.

FEC consists of forwarding additional data so that the destination can reconstruct the original information even if losses occur. In this case latency is less influenced by network dynamics and becomes more predictable. There are two typical approaches to embody FEC techniques in ALM solutions [14]: (i) *End-to-End FEC*, i.e., encoding is performed only by the multicaster, and (ii) *Link-by-Link FEC*, i.e., every node performs encoding and decoding so to tolerate losses on each link of the multicast tree. However, FEC has not found an enthusiastic use in group-aware communications, like the one performed by publish/subscribe middleware, due to the intrinsic drawbacks of these two approaches. On one hand, End-to-End FEC selects the redundancy degree with respect to the loss pattern experienced along the path of worst quality. So, if only few paths exhibit heavy losses (this is likely to happen in overlay networks), the multicaster has to generate a very large number of repair packets. Such overwhelming redundancy may overload the nodes and/or cause serious congestion of the network. On the other hand, Link-by-Link FEC causes strong degradations in performance due to the continuous execution of the two coding operations at every overlay node. In [15] we have proposed a novel FEC technique by allowing only a subset of interior nodes, called *codecs*, to perform encoding (*Network-Embedded FEC* - NE-FEC) so to have a more flexible control on the redundancy than End-to-End FEC and reduce the performance penalties of Link-by-Link FEC.

We have performed a simulation study to assess the quality of our approach that combines Multiple Trees and NE-FEC. In Fig. 2, we have compared the timeliness and reliability degrees achieved by our approach to the widely adopted retransmission-based schema (called *Gossiping* [7]). It is evident that our approach offers a more stable and scalable delivery time even if the network is affected by message losses. However, it is not able to provide complete reliability due to multiple paths that are not completely disjoint or failures of the FEC strategy. Therefore, we propose to team up our proactive with a reactive one as gossiping. In this case, we can observe a slight variation in the timeliness guarantees but a strong improvement of the reliability degree, as shown in Fig. 3.

Some of the available publish/subscribe services adopt serialization formats that can be defined as *binary*, and a practical example is the *Common Data Representation* (CDR) [22], adopted by all products compliant to DDS specification.

Flexibility vs. Scalability

Binary formats are based on a positional approach: serialization, and relative de-serialization, operations are performed according to the position occupied by data within the byte stream. To better explain how binary formats work, let consider a publisher and subscriber exchanging a certain data instance. The publisher converts the content of each field in bytes, and stores them in a byte stream, which is treated as a FIFO queue. On the subscriber side, the application feeds data instances with information conveyed by received byte streams. Specifically, knowing that the serialization of the first field of type T requires a certain number, namely n, of bytes, the subscriber extracts the first n bytes from the byte stream. Then, it casts such n bytes in the proper type T and assigns the obtained value to the field in the data structure. Such operation is repeated until the entire data instance is filled.

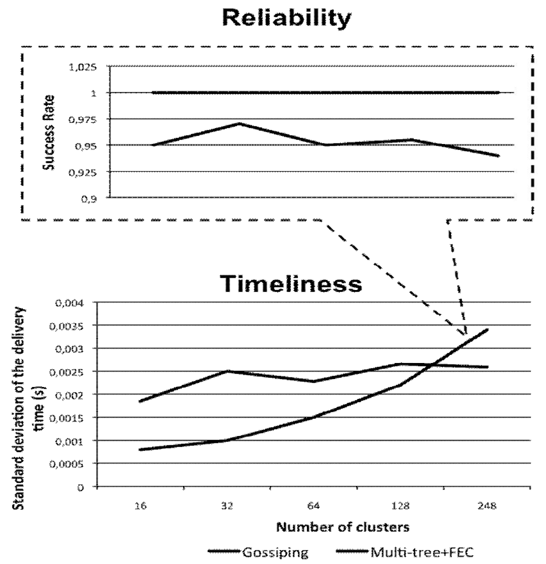

Figure 2. Timeliness and Reliability of joint Multiple Trees and NE-FEC compared by gossiping

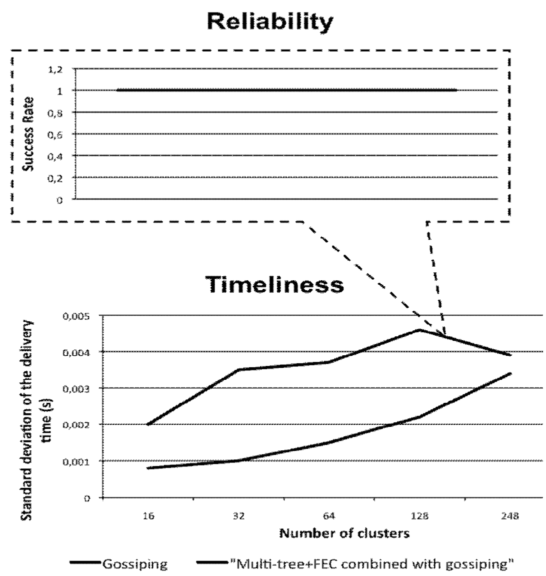

Figure 3. Timeliness and Reliability of joint Multiple Trees and NE-FEC compared by gossiping

It is quite evident that CDR does not support a flexible communication. In fact, the ability of the subscriber to comprehend the received message, i.e., to obtain the original data instance starting from the received byte stream, is coupled to the knowledge of the data structure on the publisher side. On the other hand, since only instance content is delivered throws the network, formats such as CDR exhibit a serialization stream characterized by a minimal size.

When a middleware solution wants to provide flexible communication, it typically uses serialization formats defined as *tree-based*, i.e., they embodies in the serialization stream not only instance content, but also meta-information, organized as a tree, about its internal structure. Such meta-information allows decoupling the interacting applications to the reciprocal knowledge of the structure of the data that they are exchanging. The most widely adopted tree-based format is *XML*, which specifies the structure of data content by a combination of opening and closing tags. In fact, there has been an increasing demand for XML-based publish/subscribe systems, which support flexible document structures and subscription rules expressed by powerful language such as XPath and XQuery [21].

Adopting XML allows the subscriber to be unaware of the data structure at the publisher side since the stream structure is no more implicit, but explicit into the tags. So, flexible communication is supported; however, such flexibility is achieved at the expenses of delivery latency. In fact, XML syntax is redundant or larger with respect to binary formats of similar data, and this redundancy may affect application efficiency through higher transmission and serialization costs. For this reasons, we have investigated the use of two lightweight tree-based formats: *JSON*[2] and *YAML*[3].

We have conducted an experimental campaign by realizing a prototype to exchange data instance of a type defined by EUROCONTROL for data distribution within the European Air Traffic Management (ATM) framework, called "*ATM Validation ENvironment for Use towards EATMS*" (AVENUE)[4] and characterized by a complex structures of about 30 nested fields and a size of about 100 KB. In addition, we have used an implementation of DDS as publish/subscribe service to exchange messages between a publisher and a subscriber. Fig. 4, a illustrates that CDR presents the highest efficiency, but it is surprising how bad the tree-based formats perform. Among the tree-based formats, the ones with the better efficiency are JSON and a compact version of YAML, while the worst efficiency has been registered for XML when using a DOM parser.

Previous experimental results have clearly proved the considerable performance overhead implied by tree-based, making them inapplicable in application scenarios where timeliness is also a key requirement to be satisfied. A possible solution to limit this drawback is to use *Data Compression* techniques. During the years, several data compression techniques have been presented by academia or industries. Such techniques can be broadly classified in two distinct classes: *lossy*, i.e., there is a probability to lose some information after the decompression, and *lossless*, i.e., it is guaranteed that information is never lost. Since we do not want to incur in any occurrence of data losses, we have preferred techniques belonging to the second class. The most used lossless compression techniques are the following ones: *(i)* optimal coding of *Huffman*, *(ii) Lempel-Ziv* (LZ) algorithm, and *(iii) Run-length encoding* (RLE). Such techniques are known to achieve between 50% and 30%

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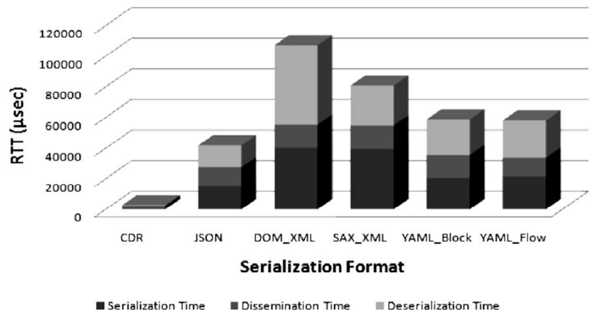
[2] www.json.org/index.html
[3] www.yaml.org
[4] www.eurocontrol.int/eec/public/standard_page/ERS_avenue.html

as compression efficiency. If an higher compression efficiency is needed, the literature is rich of *hybrid schemas* that combine the previous techniques: *(i) zlib*, which adopts the ``DEPLATE" method to combine LZ and Huffmann Coding, *(ii) bzip2*, which use the Burrows-Wheeler block sorting technique and Huffman coding, and *(iii) Lempel-Ziv-Oberhumer* (LZO) algorithm, which is similar to zlib but faster.



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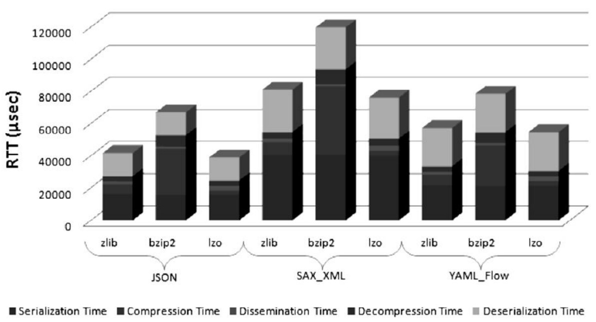

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Figure 4. Performance of tree-based formats compared with CDR with or without data compression

We have conducted the same experiments as before by applying hybrid data compression schemas, whose outcomes are illustrated in Fig. 4, b. Such experiments proved that even using data compression, we are not able to observe a sensible improvement in performance than the case of using CDR. In fact, the advantage of reducing the bytes exchanged over the network is mostly nullified by the overhead to perform compression and decompression operations. We can conclude that when timeliness is a major concern, jointly with flexibility, tree-based formats do not represent a feasible solution, so further research is need to realize a flexible binary format.

Conclusions

In this paper we have presented some investigations that are being conducted at the University of Napoli aiming at addressing the major limitations of publish/subscribe middleware when applied to LCCI. We have illustrated a hybrid P2P topology so to fragment the overall LCCI is several domains where a given reliability strategy is properly selected with respect to the experienced network conditions. Moreover, we have discussed how to jointly support reliability and timeliness by means of proactive methods teamed up with a reactive one. Then, we have concluded by analyzing the use of tree-based formats, as XML, to support flexibility and proving that such formats are unsuitable in the context of LCCI, so further research efforts are needed.

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Рецензент: д-р техн. наук, профессор, заведующий кафедрой компьютерных систем и сетей В.С. Харченко, Национальный аэрокосмический университет им. Н.Е. Жуковского «ХАИ», Харьков.

РАСПРЕДЕЛЕНИЕ ДАННЫХ ДЛЯ ПРОГРАММНЫХ СИСТЕМ КРИТИЧЕСКОГО ПРИМЕНЕНИЯ

К. Эспозито, Д. Котронео, С. Руссо

В настоящее время в некоторых инновационных промышленных проектах разрабатываются современные сложные распределенные системы критического применения, состоящие из объединений гетерогенных компонентов масштаба Интернет. Принятая архитектура промежуточной платформы (middleware) базируется на публикации модели взаимодействия с присущими существенными разделяющими свойствами и имплицитными широковещательными мощностями. Такие критические системы требуют опубликованного middleware для совместной поддержки нескольких нефункциональных требований, таких как надежность, актуальность, масштабируемость и гибкость для предложения соответствующей политики качества обслуживания. Между тем, текущие продукты middleware обнаруживают некоторые ограничения при поддержке нефункциональных требований. Данная статья детально описывает данные ограничения и представляет перечень альтернативных решений для их преодоления.

Ключевые слова: широкомасштабные сложные критические инфраструктуры (LCCI), публикуемые промежуточные платформы, надежность, масштабируемость.

РОЗПОДІЛЕННЯ ДАНИХ ДЛЯ ПРОГРАМНИХ СИСТЕМ КРИТИЧНОГО ЗАСТОСУВАННЯ

К. Эспозіто, Д. Котронео, С. Руссо

В даний час у деяких інноваційних промислових проектах розробляються сучасні складні розподілені системи критичного застосування, що складаються з об'єднань гетерогенних компонентів масштабу Інтернет. Прийнята архітектура проміжної платформи (middleware) базується на публікації моделі взаємодії, що характеризується істотними розподільними властивостями й імпліцитно широкомовними потужностями. Такі сучасні критичні системи вимагають опублікованого middleware для спільної підтримки декількох нефункціональних вимог, таких як надійність, своєчасність, масштабованість і гнучкість для пропозиції відповідної політики якості обслуговування. Тим часом, поточні продукти middleware мають деякі обмеження щодо підтримки нефункціональних вимог. Дана стаття детально описує ці обмеження і представляє перелік альтернативних рішень для їх подолання.

Ключові слова: Широкомасштабні комплексні критичні інфраструктури (LCCI), проміжні платформи з відкритим кодом, надійність, своєчасність.

Esposito Christian – PhD, PostDoc Fellow, Consorzio Interuniversitario Nazionale per l'Informatica (CINI) and Department of Computer and Systems Engineering (DIS) of the University of Napoli Federico II.

Cotroneo Domenico– PhD, Assistant Professor, Department of Computer and Systems Engineering (DIS) at University of Napoli Federico II.

Russo Stefano – PhD, Professor, Department of Computer and Systems Engineering (DIS) at University of Napoli Federico II.