Towards a Scalable and Interoperable Global Environmental Sensor Network using Service Oriented Architecture

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***Abstract*—Sensor networks are critical infrastructures for monitoring environmental variables, allowing evaluation of long-term trends and changes in the interaction of atmospheric, ecologic, and hydrologic processes. However, due to lack of coordination between large-scale environmental observation systems that have been set up around the globe, the wealth of information collected by sensor networks is not exploited to its full potential. Since there is no central organization tying these various systems together, data acquisition and dissemination methods are inconsistent and public accessibility to these observation systems is restricted to the methods chosen at the individual project level. The ability to easily discover, access, and interact with observational instruments and use real-time sensory data spread across different environmental observatories is limited. Interoperability of sensor network assets is essential to producing improved projections, models, analyses, and assessments at a global scale. To this end this paper presents the architectural design for a scalable, interoperable and real-time environmental sensor network. The proposed architectural design also provides support for dynamic reconfiguration of sensors in response to changing environmental conditions, and facilitates secure sensor access and delivery of observations to a distributed community of users using standardized mechanisms based on Open Geospatial Consortium standards. The outlined architecture uses an Event-Driven Service Oriented Architecture, with Enterprise Service Bus as its backbone messaging transport layer.**

I. INTRODUCTION

Environmental sensor networks are essential infrastructures for establishing baseline conditions in specific ecosystems and allowing observation of trends over time related to atmospheric, hydrological, and ecological variables. A large number of diverse observatory systems have been deployed globally to measure these and other environmental parameters. However, the observation capabilities of these systems are driven mainly by local requirements to satisfy particular project monitoring needs, without plans for coordination with other geographically scattered sensor network systems. Presently, the majority of these ad-hoc observational networks do not interoperate with each other because the sensors and field instruments are accessible only by disparate and proprietary software interfaces. Each observatory functions as an isolated sensor network and provides access to long-term sensory data via its data portal. Scientists synthesize this data from different sites to discover trends and relationships, spending significant amounts of time sorting and extracting relevant data. Interoperable observatory systems are necessary to facilitate discovery, dynamic capture, and real-time integration of sensory information from multiple disciplines to answer research queries in forms useful to educators, domain specialists, policy makers, and other stakeholders [1] at a national and global level. Interoperability also provides the capability to access near real-time sensor data corresponding to transient phenomenon or events of interest, thereby assisting first responders with more meaningful analysis of the anomalous state of the environment reported manually or by an automated trigger. The lack of interoperability between sensing systems leads to a lack of efficiency and limited use of the enormous amount of real-time sensory data, which has an important role to play in global environmental research [2]. Therefore, it is critical for the sensor community to move away from the use of customized or proprietary interface mechanisms for access and control of sensors, and adopt standardized interface mechanisms so that the sensor networks are not isolated from other national or global observational systems. To this end, this paper presents an overview of the architecture for an environmental sensor network that is a capable of addressing the aforementioned needs.

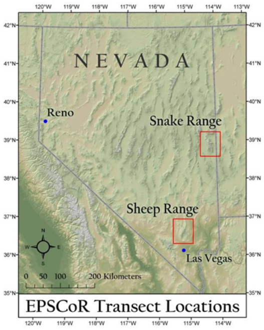

Fig. 1. Nevada Transect Locations

This paper discusses the high-level architecture in context of Nevada's EPSCoR environmental monitoring network. Nevada's EPSCoR sensor network comprises of two transects, as shown in Fig. 1, covering key parts of Nevada's basin and range topography. The first transect is located in Southern Nevada and covers the Spring and Sheep Mountains, two of the most biologically diverse mountain ecosystems in the region. The second transect is located in the Great Basin National Park and reaches the ancient bristlecone pine stands on Mt. Wheeler. These transects consists of 12 individual station locations and each of these stations is instrumented with an array of atmospheric, ecologic, and hydrologic monitoring sensors. The proposed architecture is designed based on the requirements of interoperability, scalability, event processing for dynamically adaptive infrastructure, and near real-time data and sensor network assets sharing with a distributed community of users. This architecture is not specific for the domain of environmental sensor networks and serves as a reference for future and existing sensor networks.

The outline of this paper is as follows: Section II briefly discusses the current landscape for sensor network infrastructures and the standard for interoperability between sensor networks. Section III presents the middleware for the cyberinfrastructure component of Nevada's sensor network. Section IV discusses the significance of the presented architecture along with concluding remarks.

II. BACKGROUND

Typically, an environmental observatory has a diverse array of sensors deployed in the field which are connected to a data logger (a hardware device deployed in the proximity of the field sensors responsible for interpreting data from sensors and storing it on the local memory card until it is transmitted it to a central receiver station). Data logger manufacturing firms (e.g., Campbell Scientific) provide software applications for the central receiver station to communicate with data loggers to collect data and control the sensors. Software development kits (SDK), for direct control of sensors and data access through a web browser interface, are also made available. Custom software modules are built around the data logger SDK to store the acquired sensory data into files or a database. The stored data is processed for quality assurance and quality control and then made available to the research community via a data portal. Fig. 2 depicts this process.

Researchers download huge data sets through the data portal (e.g., WCRP's CLIVAR [3], WRCC [4]) for available coverage areas and time periods. Scientists then filter through the data sets to extract relevant data for their experiments and integrate the data from various portals to conduct research. Development and exchange of data and models among scientists from different disciplines and among various environments are often time consuming and detract from synthesis and interpretation of data [5]. Some data portals supply a data catalog for download of derived data sets and a nested collection of data from multiple sources (e.g., NCAR's Community Data Portal [6]). Various other portals provide support for selective data download by allowing users to choose parameters for data retrieval (e.g., LTER's Climate and Hydrology data portal [7]). Some advanced data portals (e.g., RENCI Sensor Data Bus [8], SAHRA GeoDB [9]) offer data web service solutions for customized data access (for a selected data variable, coverage area and time period etc.) from an enormously large set of measurements stored in the database. However, researchers are still restricted to use the static data set made available on the data portal. Support for real-time and/or dynamic data acquisition with autonomous response capability to specific science-driven events, and real-time data processing using complex event processing is offered by very few observation networks (e.g., SCCOOS [10], CASA-LEAD [11], and NASA's EO-1 [12]).

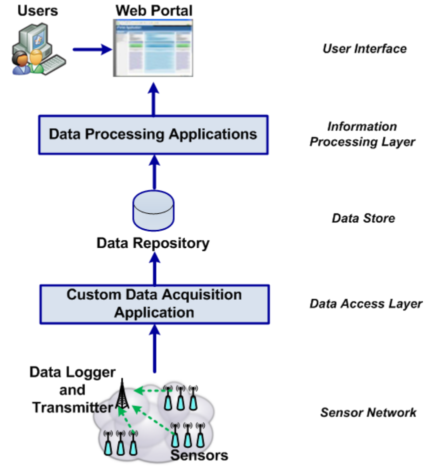

Fig. 2. Typical Architecture of an Environmental Sensor Network

Since sensor networks are owned by different communities, it is observed that different sensor network portals portray different capabilities such as - (i) access to archived, consolidated, processed, or real-time data, (ii) event-driven data collection, (iii) complex event processing (CEP) of environment monitoring data, (iv) dynamic, autonomous reaction of sensors to environment changes. It is rare for any sensor network to provide all these capabilities. The current state-of-the-art does not facilitate querying different environmental sensor networks and aggregating real-time, event-based observations from several observatories, to study the state of the environment on a global, national, state, or regional scale ([13], [14], and [15]). Furthermore, the support for standardized web-enabled operation of field sensors and instruments for time-critical events is also lacking at present in most observatories. These limitations exist because environmental scientists build sensor network infrastructures without planning integration paths with other researchers and their networks, and do not consider using emerging standards for sensor interfaces and technical architecture. The Open Geospatial Consortium (OGC), a global standards organization with representatives from industry, government and academic/research institutions around the world, has developed the Sensor Web Enablement [16] (SWE) suite of standards to overcome these limitations. Adhering to SWE standards reduces the complexities in integrating disparate sensor network systems. However, the adherence of one network to SWE standards is not sufficient. The vision of querying different environmental sensor networks over the web to retrieve timely, comprehensive, and selective observations can only be realized when all or a majority of observatories implement SWE standards to expose their sensor assets over the web. The next section presents an architecture that assists towards realization of this vision.

III. ARCHITECTURE

A. *Design Considerations*

The architecture presented here serves as a middleware component for the cyberinfrastructure of Nevada's EPSCoR ecological sensor network. The objectives of the architectural design are: (i) to facilitate real-time, seamless integration with heterogeneous sensor networks, (ii) to facilitate efficient addition of new sensors and instruments to the existing observatory, (iii) to provide support for event processing, enabling an adaptive sensor network infrastructure that can dynamically reconfigure in response to changing environmental conditions, and (iv) to assure secure sensor access and delivery of observations to a distributed community of users using standardized mechanisms.

The design incorporates the Open Geospatial Consortium's Sensor Web Enablement [17] suite of standards for web-enabled discovery, use, and control of sensors, and access to their observation data in standard encodings. The design is based on an Event-Driven, Service Oriented Architecture (SOA) that relies on Enterprise Service Bus (ESB) [18] (an emerging technology that provides a loosely coupled, flexible, scalable, interoperable, reliable, and secure solution with high availability and usability). This architectural design will serve as a reference for future web-enabled (i.e. interoperable through the use of web services) autonomous sensor networks.

As demostrated by Fig. 2, typical sensor network architectures require additional resources and effort to write a new custom data acquisition application when adding a new sensor network, if the data logger manufacturer for the new site is different from what is already in use at the existing sites. This newly added application requires writing additional code for storing data into the database to accommodate different types and format of data supported by the new brand of data logger installed in the field. Furthermore, the changes required to the cyberinfrastructure component are not just limited to the Data Access Layer, but propagate all the way up to the user interface layer since the subsequent layers need to be changed as well to accommodate the new data. This high ripple effect is mainly due to the fact that the system components are tightly coupled with each other. The use of a standards based data model (OGC SWE data encodings) and an ESB (that handles data transformation from custom formats to the standards based format that is stored in the database) eliminates the tight coupling between different layers of the cyberinfrastructure.

Fig. 3 illustrates the scalability aspect of the system architecture. Addition of new sensor networks requires the following two steps - i) configuration of the ESB adapter component [18] that fetches data in its proprietary format from the data logger; and ii) definition of the data transformation component that maps proprietary data to the standard format which resides in the database, if the data logger manufacturer is different. The data processing applications and user interface layer are isolated from these changes as they are linked only to the database. This results in a loosely coupled system.

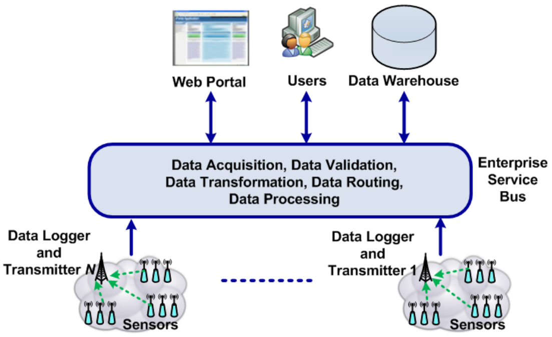

Fig. 3. Scalable Architecture using ESB

B. *System Components*

The project's architectural implementation relies on emerging technologies EDA (Event Driven Architecture), SOA, ESB, CEP (Complex Event Processing) and standards (SWE, XML). Using an EDA coupled with SOA and ESB, as its backbone, allows for interoperability of the sensor network with other sensor networks. The SWE suite of standards comprises of two blocks: the information model (O&M, SensorML [19]) which consists of conceptual models and encodings for sensor descriptions and sensor observations, and the service model (SOS [20], SES [21], SPS [22], WNS [23], CSW [24]) which provides standard interface definitions for web services. The presented architecture takes a service strategy approach beginning with how services can replace legacy code to reduce the overall costs of cyberinfrastructure development and maintenance. The architectural diagram as shown in Fig. 4, provides a conceptual view of how the cyberinfrastructure is designed in order to create a robust, secure, scalable, high-performance environment for the sensor network.

A description of the components that constitute the system architecture is as follows.

1) Enterprise Service Bus (ESB): ESB provides a messaging bus architecture through which disparate services connect and communicate. An ESB fuses message-oriented, event-driven and service-oriented strategies for integrating heterogeneous applications and services.

ESB supports different transport protocols to connect to services, provides data transformation and routing, content based routing using publish-subscribe engine, supports reliable, secure messaging and transaction services, and facilitates building of services as well as workflows. These features are required to implement OGC SWE standards based sensor interfaces and services. ESB eliminates a direct connection between the service consumer and the service provider, facilitates separation of application logic from the data model and the integration logic thereby minimizing the impact of changes in

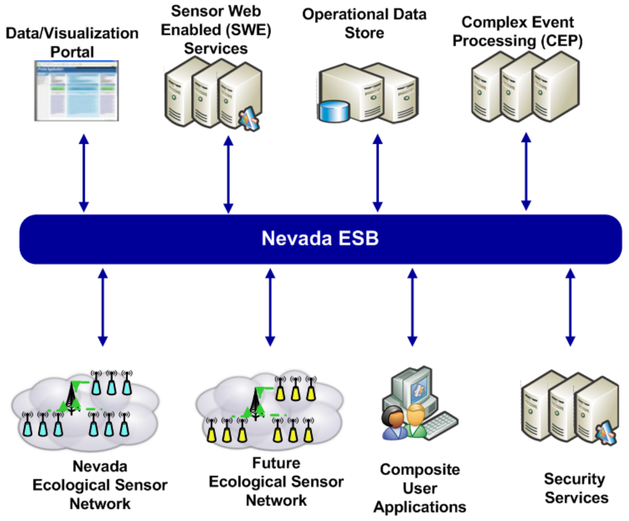

Fig. 4. Scalable, Real-Time and Interoperable Architecture

one service on the other services, hence support adaptability to change and loose coupling.

2) Nevada Ecological Sensor Network: The Nevada environmental sensor network consists of 12 individual station locations spread across two separate mountain ranges in eastern and southern Nevada. These sites are instrumented to measure key environmental variables and biological indicators of ecosystem responses to regional climate change. Each of these stations is equipped with an array of atmospheric, ecological, and hydrological monitoring sensors, including air temperature, humidity, wind speed/direction, incoming/outgoing radiation, precipitation, soil moisture, soil temperature, and snow depth. Select stations include controllable web cameras, vegetation sap flow sensors, and tree growth increment monitors. The various sensors are attached to data loggers. Campbell Scientific's data logger and the software development kit (SDK) is responsible for direct control and configuration of sensors and data access using TCP. The data logger is connected to the ESB. Any sensor change is termed as an event for real-time processing purposes. Custom software modules are built around the data logger SDK to publish the sensory data as sensor events to the ESB. Open standards such as WS-Eventing and WS-Notification, Real Simple Syndication (RSS) or Atom feeds, Extensible Messaging and Presence Protocol (XMPP) can be employed to support delivery of sensor information or event notifications to the ESB.

3) Sensor Web Enablement (SWE) Services: Sensor Web Enablement (SWE) standards introduced by the Open Geospatial Consortium (OGC) make feasible the interoperability of diverse sensor networks. The standard provides specifications that allow sensors and field instruments to be discovered, accessed and controlled over the web, irrespective of the type of sensor and the manufacturer. The system must implement SWE service interfaces that rely on fetching archival data from the data warehouse and near real time data from the ODS. SWE services required to be implemented are listed below:

- Sensor Observation Service (SOS) - service interfaces to interrogate information about sensors and access sensor data.
- Sensor Event Service (SES) - service interfaces for subscription and publication of alerts from sensors if user defined criteria are matched. SES also enables on-demand and near real-time sensor data mining and fusion.
- Sensor Planning Service (SPS) - service interface to help users build a feasible sensor collection plan and to schedule requests for sensors and sensor platforms.
- Web Notification Service (WNS) - service interfaces for asynchronous delivery of messages or alerts from Sensor Alert Service (SAS) and SPS web services and other elements of service workflows.
- Catalogue Services (CSW) - service interfaces to support the ability to publish, access, and search collections of descriptive information for service type of interest.

4) Operational Data Store (ODS): An operational data store is a database designed to integrate data from multiple sensors or heterogeneous sensor networks. The ODS is designed to subscribe to cleansed/processed sensor information, which is published to the ESB from the CEP engine. ODS resides on an Extract Transform Load (ETL) server so that the sensor data can be transformed to normalized SWE O&M data format and this data is then loaded into the data warehouse on a less frequent schedule. The data warehouse may consist of multiple data marts to provide data for different sensor applications. The ODS stores limited sensor history data that is captured real time or near real time as opposed to the much greater volumes of data stored in the data warehouse. ODS provides data for near real time queries whereas data warehouse provides archived or longer history sensor data to higher levels of aggregation and more advanced analysis. ODS is thus one of the critical components of the system to provide near real time capabilities and to reduce the sensor data latency. An ETL server complements the functionality of ESB by providing batch data transformation on large data sets. Data transformation is required to format sensor data from different proprietary sensor formats into O&M data format and format sensor metadata in to SensorML format.

5) Complex Event Processing (CEP): CEP provides a complete platform for building real-time, event driven applications. It consists of a real-time event correlation engine and event based rules, encoded in the Event Pattern Markup Language (EML), are loaded in the engine to pre-process or mine the sensor data. CEP engine subscribes to events published to ESB from the data loggers for rule based sensor data preprocessing or real-time sensor mining. Multiple levels of inference can be used to extract information from the sensor event cloud or sensor event stream. The lowest level would include cleansing sensor data for upstream processing. CEP enables publishing of refined, inferred sensor alerts based upon certain criteria such as a measured value exceeding a certain threshold or detection of an event from a single or multiple observations to the ESB. Whenever filtering criteria matches are discovered, a notification is sent to the subscriber, using asynchronous, push-based communication mechanisms.

6) Security Services: When a cyberinfrastructure is used to monitor the sensor network and even control and configure the sensors in real time, security is a critical component of the proposed architecture. Security services offer services and applications the ability to authenticate, authorize, encrypt/decrypt messages, and sign messages/verify signatures. Authentication is the process of positively identifying the users ensuring that the users are who they claim to be. Authorization defines which resources and operations the authenticated user is allowed to access. The authors propose using a Role Based Access Control (RBAC) security model. Role is a collection of tasks that a user must have to do that job. Users and groups are assigned to roles. Roles can be provided either in a centralized or a federated directory server and authenticated using Lightweight Directory Access Protocol (LDAP). Users external to the system are authenticated using directory store located in the DMZ (Demilitarized Zone). Securing at the transport level ensures that data remains private and confidential, and that it cannot be viewed by eavesdroppers armed with network-monitoring software. Secure Sockets Layer (SSL) is a public key-based security protocol that provides authentication, confidentiality, and data integrity at the transport level. Integrity ensures that data is protected from accidental or malicious modification while in transit. Security at the message level is achieved by encrypting the data content and then signing the message body. Security services must supports standards such as Security Assertion Markup Language (SAML) and WS-Trust.

7) Composite User Applications: A composite user application is built by integrating SWE web services, models, projections and environmental change analysis tools. Security services can be been assembled to provide new applications on different devices such as thin clients or smart phones.

8) Future Ecological Sensor Network: This component indicates future expansion of the existing network. If the same manufacturer of data logger as the current network is used, no additional work is required to publish sensor events to ESB. Thus, sensor networks can simply plug and play into the ESB. The architecture allows integration with other environmental observatories as well (such as Europe's *SANY* or *HMA* network, Australia's *CSIRO* or Japan's *CCIMAN* initiative as shown in Fig. 6) which use sensors of different kind and use data loggers from different manufacturers. Each manufacturer provides its own proprietary sensor acquisition data format through the data logger. Implementing open standards such SWE standards for each of these sensors by different manufacturers and making this implementation open source will thereby allow wider acceptance by the community and enable plug and play of sensor networks in Nevada ESB and other ESBs as well. In the absence of implementation of SWE standards as sensor data services, each system will have to use the data logger manufacturer's SDK to plug the sensors in to their system. This tightly couples the sensors to the system and each time there is addition of new sensors there is a high ripple effect in terms of changes to the system to add the new network. One of the main advantages of SWE services is to provide sensor data and sensor parameters or metadata without the need for a priori knowledge of the sensor system. Since data logger manufacturer's use proprietary formats, custom code will need to be wrapped around the manufacturer's SDK to publish sensor data as events to plug the sensor network into ESB. The sensor events can then be preprocessed using Complex Event Processing (CEP) engine, aggregated into ODS and periodically loaded into the data warehouse using ESB as the message transport layer. Composite user applications can query near real time or archived sensor data using SWE web services through the ESB.

9) Data/Visualization Portal: The portal is the one stop shop for both internal and external secure access to the sensor network data and services. The portal invokes the SWE services.

C. Technology Stack

The stack of technologies required for implementation of this design and the relationship between each technology is illustrated by Fig. 5

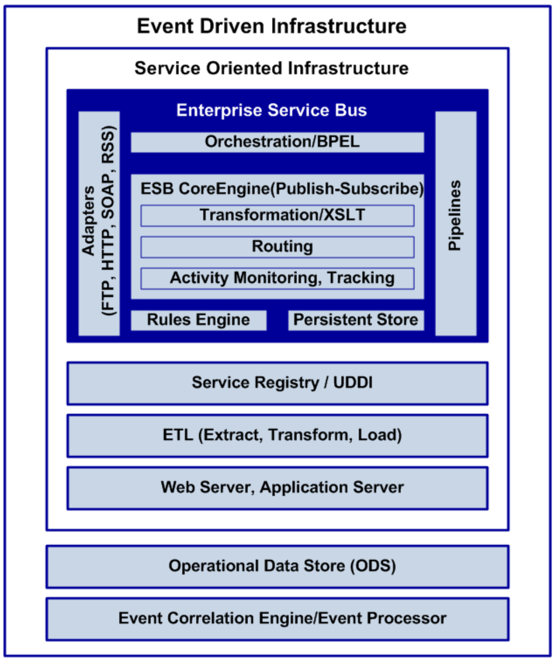

Fig. 5. Technology Stack

IV. SUMMARY AND CONCLUSIONS

Over previous decades most climate scientists have built ad-hoc networks without planning integration paths with other researchers and their networks. Most newer climate sensor networks fit this model by utilizing proprietary software for sensor data acquisition, sensor control, and monitoring. Interoperability of environmental observatories provides comprehensive and selective observations to perform adaptive experiments on globally diverse, dynamically consolidated data sets. While there is literature ([25], [26]) citing the use of ESB and SWE to achieve interoperability between sensor networks, the novelty and contribution of this paper lies in the aspect that it offers an architectural design that supports scalability, interoperability, real-time dynamically adaptive, event-driven data collection and sensor configuration capabilities that facilitate climate change science research at a global scale.

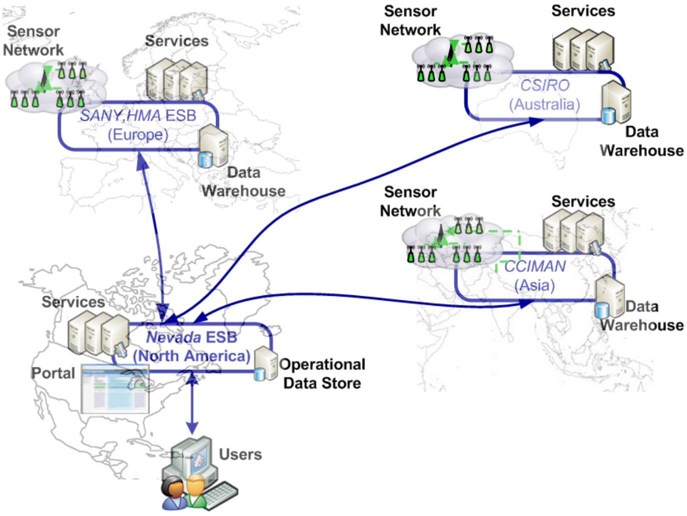

Fig. 6. Global Environmental Sensor Network

The proposed cyberinfrastructure developments will facilitate better use of existing investments and enable atmospheric scientists, ecologists, climatologists, hydrologists, engineers, social scientists, economists, and others to more effectively share non-traditional sensory data, and to develop novel models and improved forecasting for new data sets. The availability of internet-enabled sensor network assets will add value to and build on the existing research work on global scale analysis of environmental processes and change. At a societal level, implementation of the proposed design will contribute towards timely capture of hazard-related events for improved environmental awareness, improved warning and forecasting systems, accurate and efficient decision making that affects public health and safety and our economic interests, and improved emergency preparedness and response (in addition to providing time and cost savings to the agencies responsible for public health and safety).

The scalability challenge for a centralized ESB architecture can addressed by the federated ESB model [27]. Federation requires a lot of coordination, transformation, routing logic, security and goverance thereyby necessitating the need for a global consortium responsible for introducing policies that allow geographically distributed services to communicate and have multiple ESB domains working together to form a single, logical ESB.

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