# Event-Driven Data Integration for Personal Health Monitoring

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***Abstract*—The emergence of biomedical wireless sensors, the wide spread use of smartphones, and advanced data stream mining techniques have enabled a new generation of personal health monitoring systems. These health monitoring systems are mostly stand-alone and are not yet integrated with existing e-Health systems, which could seriously limit their large scale deployment. In this paper, we propose an architecture for data integration within an electronic health care network based on extending the traditional SOA approach with support for complex event processing and context awareness. This architecture also facilitates integrated business performance management against quality of care targets. A detailed health monitoring scenario for the care of cardiac patients is used to illustrate system requirements and to validate the proposed architecture. The expected benefits of our approach include a higher quality of care, reduced costs for health service providers and a higher quality of life for the patients.**

***Index Terms*— e-Health, wireless sensors, smartphone, machine learning, context awareness, data integration, event-driven architecture, complex event processing**

## I. Introduction

A significant shift is happening in the way healthcare is delivered: we are moving from an era where Health Service Providers (HSP) are working mostly in isolation to a mode of collaborative care where multiple HSPs will be working more closely together on a patient's clinical case. This requires a higher level of integration and interoperability between information systems than ever before.

In parallel with this shift, the emergence of biomedical wireless sensors, the wide spread use of smartphones, and advanced data stream mining techniques have enabled a new generation of personal health monitoring systems. These are used for instance, to remotely monitor the health of chronically-ill or elderly patients at home, making possible a much higher quality of life. These systems are currently at the research stage with some initial clinical trials. A critical requirement is for interoperability with existing e-Health systems; the personal health monitoring systems are mostly stand-alone and are not yet integrated with existing e-Health systems, which could seriously limit their large scale deployment.

In this paper, we propose an architecture for data integration of personal health monitoring systems within an electronic health care network based on extending the traditional SOA approach to B2B (business to business) networks with support for complex event processing and context awareness. This architecture also facilitates integrated business performance management against quality of care targets. This approach advocates lightweight system interoperability with loose coupling between systems, based on events.

A detailed health monitoring scenario for the care of cardiac patients is used to illustrate system requirements and to validate the proposed architecture. The expected benefits of our approach include a higher quality of care, reduced costs for health service providers, and a higher quality of life for the patients.

The remainder of this paper is organized as follows. Section 2 gives an overview of next-generation Health Monitoring systems and of the organizational shift taking place currently. Section 3 presents the Health Monitoring scenario which will be used to describe the architecture. Section 4 presents our proposed architecture for Context Awareness and Complex Event Processing to support data integration within an electronic healthcare network. Finally, Section 5 discusses the approach and Section 6 presents future work in our early stage project.

## II. Background

### *A. Shifting Organizational context for collaborative care: Example of Ontario, Canada*

In Canada, healthcare is managed by each province. The province of Ontario has recently created 14 Local Health Integration Networks (LHINs) to provide better coordination and service delivery to patients [22, 23].

In Ontario, the LHINs are responsible for the following programs and services: hospitals, community care access centers (home care), community support service organizations, addictions and mental health agencies, community health centers, and long-term care homes.

The Ontario Ministry of Health and Long-term Care, which funds provincial healthcare programs, has retained direct responsibility for the following programs and services: individual practitioners and family health teams, ambulance services, laboratories, provincial drug programs, independent health facilities, and public health.

This new organization seems to be representative of a global trend where regional healthcare management is preferred to a centralized model, in order to achieve the objectives of better quality of life for patients, better quality of care by medical staff, and significant cost savings for Health Service Providers. However, this patient-centered organization requires an even higher


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level of interoperability between information systems than what has been designed so far.

### *B. Current Health Monitoring systems*

Current health monitoring systems are based on portable recorders (for example, Holter Monitoring to continuously record the heart rhythms of cardiac patients) capable of recording health data collected by medical devices and downloaded into an application server after a few days. The server then does the off-line data analysis. These systems are now being replaced by a new generation of continuous health monitoring systems based on wireless sensors located on the patient's body or clothing.

### *C. Next-generation Health Monitoring Systems*

Health monitoring is a generic function in applications like chronic disease management, emergency response, homecare for the elderly, and palliative care. It's a critical foundation for telemedicine.

During the last few years, significant progress has been made in wearable or on-body wireless sensors [2, 4, 6, 7, 8, 9, 10,11, 12, 15, 16, and 17]. Similarly, smart phones are frequently used as a Personal Heath Monitoring System (PHMS) and as base stations in a wireless sensor network, as described in [1, 3]. Finally, advanced machine learning techniques have been developed for data stream mining in order to process the continuous, massive, temporally ordered, and fast changing flow of data coming from wireless sensors [5, 14, 18, 19, and 20]. Health monitoring systems are typically based on the concept of closed-loop disease management [9].

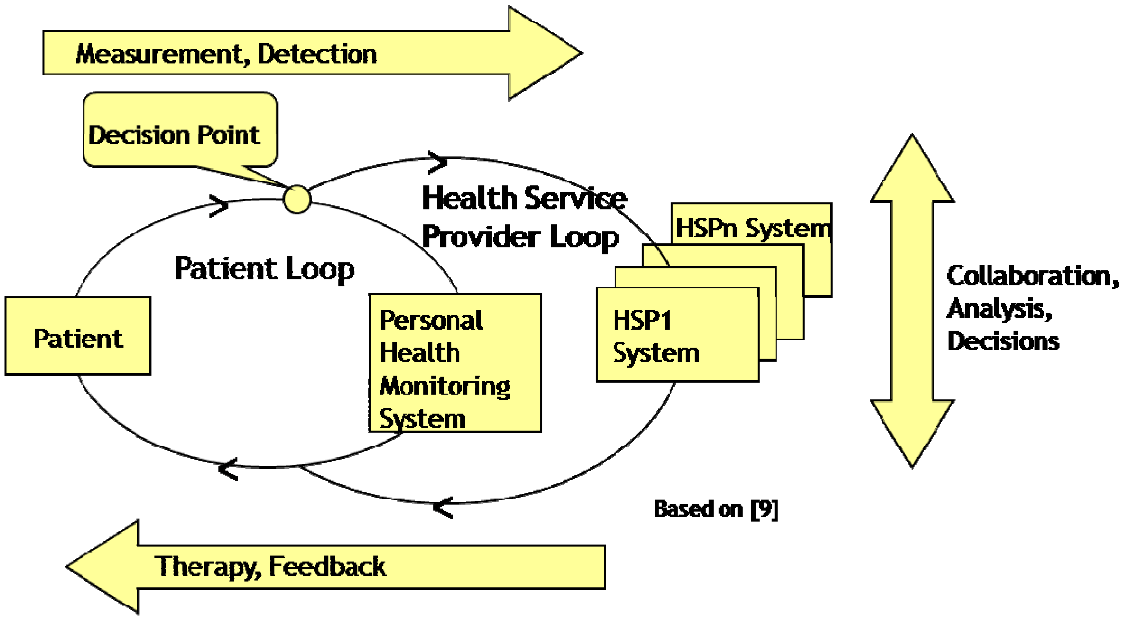


Fig. 1. Closed Loop Disease Management

One critical requirement is to provide system interoperability for seamlessly connecting the "Patient Loop" to the "Health Service Provider Loop", particularly in terms or recognizing a "Decision Point" as shown in Figure 1. The health service provider loop is extremely complex as it requires integrating multiple processes and data across different organizations in an electronic healthcare network.

The MyHeart [4] and HeartCycle [9] projects are widely considered to be pioneers among the next-generation Health Monitoring Systems. Our project follows their architectural approach with the intelligence being distributed between the sensors, the smart phone and the HSP server. One of our contributions is in event-driven interoperability between the Personal Health Monitoring System and the HSP system; another is in Context Awareness as described below.

### *D. Data Integration in an Electronic Healthcare Network*

The adhoc and event-driven nature of electronic healthcare networks present unique challenges for data integration. The dynamic nature of such networks requires a flexible, reliable communication pattern and data sharing infrastructure not limited by transaction-specific restrictions associated with traditional integration approaches. Service Oriented Architecture (SOA) [30] through web services is emerging as the standard framework for systematic and extensible machine-to-machine interaction on the Internet. Unfortunately, SOA is still limited by a point to point messaging framework that often entails unnecessary procedural interaction, data polling, and strong coupling of applications.

Event-driven architecture [32] on the other hand is characterized by its ability to decouple service providers and consumers through messages [33]. That is, producers and consumers of data are contextually coupled by the data exchanges and not procedural calls. Publish/subscribe [31] is an event-driven model that allows many clients to subscribe to the same service, and have the information sent to them as messages as they become available. The message broker acts as a central application hub for routing messages to subscribers. It supports asynchronous "push" communication and can perform message translation and formatting for heterogeneous subscribers [34]. Message brokers interconnect heterogeneous applications like CRM, SAP, SCM, e-Procurement, including legacy systems and databases.

A framework for B2B healthcare data integration is introduced in [24] and [25] that uses declarative policies to combine the communication flexibilities offered by SOA and the event-driven communication pattern of publish/subscribe in one data sharing architecture. Important considerations for this architecture include communication patterns, methods of interaction, security and privacy of data, distributed resource management, performance, and Quality of Service (QoS) for message delivery service quality

## III. Health Monitoring scenario

We now present a health monitoring scenario to illustrate the requirements for data integration of personal health monitoring systems in an electronic healthcare network that our proposed architecture addresses. This fictitious scenario describes the care of a cardiac patient within the healthcare organizational context of the Province of Ontario, in Canada.

1. A Patient, in his 60s, has a high cholesterol level, high blood pressure, and is unable to quit smoking. His family doctor has recently come to the conclusion that he has a high risk of heart attack, and has decided to have him monitored continuously using a new health monitoring service set up by the local LHIN in a community health center. The center is connected to the local hospitals, a Heart Institute, the family doctor, emergency response paramedics, and Patient's caregiver (his daughter).
2. The Patient is equipped with wearable and on-body wireless sensors connected to his smartphone which is a Personal Health Monitoring System (PHMS). His house is also equipped with fixed sensors wirelessly connected to the smartphone. The PHMS had been personalized for the Patient's medical condition; the monitoring parameters have been uniquely optimized for the Patient via a machine learning algorithm implemented on the device.
3. There has been a heavy snowfall the night before. The Patient, who has to meet with a friend, decides to clear the snow from his driveway. The PHMS has recognized that he is engaged in an intense physical activity, and has adjusted the monitoring parameters (measurement frequency, analysis time window, ECG correlation with respiration rate and stress level, blood pressure correlation with outside temperature and effort level).
4. Having cleared his driveway, the Patient takes his car and drives to his friend's place. The driving is stressful because of the snow accumulation. He starts feeling shortness of breath. His smartphone rings, and automatically answers with the loud speaker put on. He hears a voice, identifying itself as the Health Monitoring Center (HMC) and asking him to find a place to park nearby. When this is done, the Doctor on the line tells him that he is having symptoms of a heart attack, and that an ambulance is on its way.
5. At the HMC, the on-call Doctor, informed by the Patient's PHMS that he has been shoveling snow in the morning and is currently driving, has decided to change the monitoring parameters because he suspects a case of STEMI (ST segment elevation myocardial infarction). The ECG sensor is now set to maximum capacity and starts sending high-definition ECG signals. Unfortunately, the Doctor's suspicion has been confirmed, and the ECG clearly shows the ST elevation. This means that the patient has to be sent to the Heart Institute immediately, not the local hospital, for an angioplasty which must take place within the next 90 minutes. The PHMS had also assessed that the Patient is currently driving, and that his daughter, a caregiver, is not nearby. With all this information, the Doctor calls the Patient whose smartphone had been re-configured for auto-answer with loud speaker on so as not to disturb his driving. The nearest Ambulance Service Provider has been contacted.
6. The ambulance arrives shortly, and the paramedics have been briefed already to 1) confirm the STEMI with an ECG done on the spot, and 2) bring the patient to the Heart Institute. While the ambulance is on its way, the PHMS is automatically re-configured to send continuous vital signs data to the Heart Institute.
7. The Heart Institute surgical team has been fully briefed on the STEMI condition and the Patient's medical history. The operation is completed quickly and successfully. The Patient's family doctor has been kept fully informed. His daughter has been informed also.
8. Finally, a Surveillance Portal at the LHIN had been collecting and correlating events related to this medical incident, and reported that the Patient's STEMI condition had been treated within the 90 minutes window target that the LHIN has set in its Service Accountability Agreement.

This scenario shows that a coordinated e-Health strategy leveraging personal health monitoring systems could help the LHIN address priorities like improved access to healthcare, chronic disease prevention and management, and care for the elderly with complex conditions. By facilitating homecare for elderly and chronic disease patients, they could also contribute positively towards decreasing waiting time at the hospitals.

## IV. Interoperability with existing e-Health systems

In this section we analyze this scenario as it relates to our proposed framework for data integration of personal health monitoring systems within a healthcare network. In particular, we show how policy-based data integration, context awareness and complex event processing play key roles.

*A. Framework*

Figure 2 gives an overview of our framework for data integration of the personal health monitoring system within a network of HSPs. The critical building blocks of our framework are:

- The sensors used to collect health-related data (physiological sensors like ECG, pulse oximetry sensors, blood pressure sensors, etc) and also context data (physical sensors like accelerometers, thermometers, etc).
- The smartphone which, together with the sensors, constitutes the PHMS. It also fulfills the role of Base Station for the sensors. Its mobility makes it key for context awareness.
- Different Health Monitoring Servers which can receive data and event notifications from the smartphone on behalf of different HSPs so each HSP can respond quickly and effectively as appropriate to the context.
- The Message Broker and Surveillance Portal [24, 25], which are part of the enabling infrastructure for the interoperability between the PHMS and the Health Monitoring Servers.

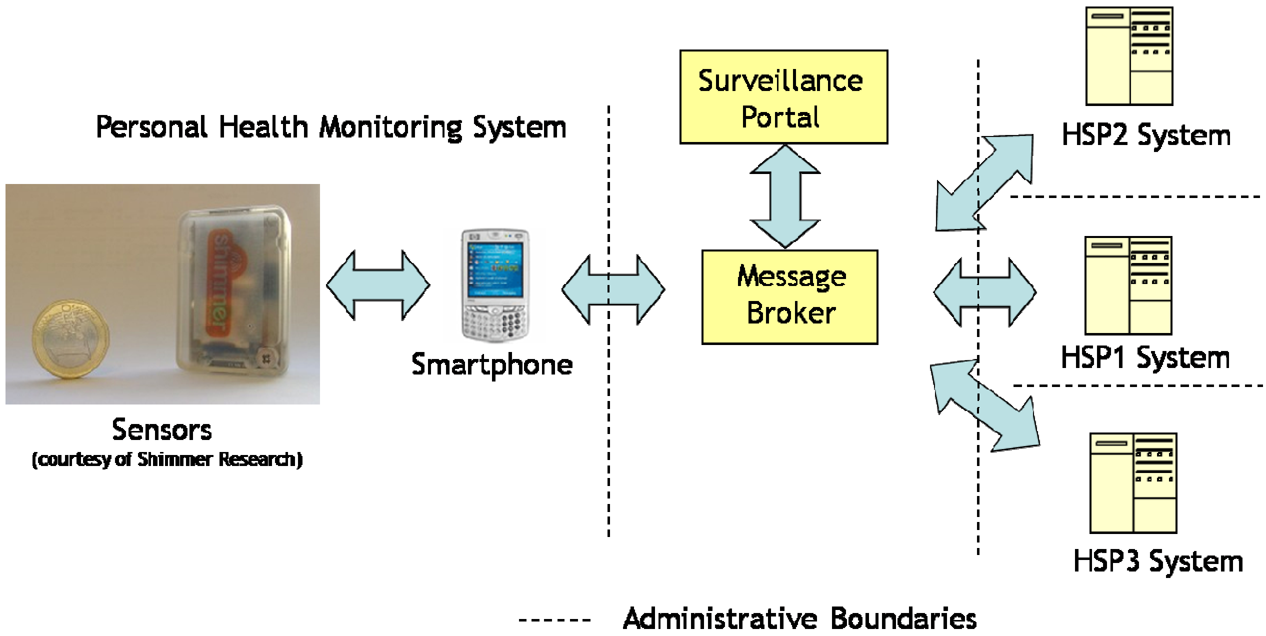


**Fig. 2. Framework Overview**

In this paper, we will not analyze all aspects of the architecture, but will focus specifically on the components required for providing context-aware, event-driven system interoperability to support data integration within a healthcare network.

*B. System Architecture*

Figure 3 shows in more detail our architecture for data integration and the role that the Message Broker and Surveillance portal play in enabling and monitoring data sharing between the PHMS and Health Service Providers (HSP).

**Personal Health Monitoring System**

The smartphone offers 2 interfaces to the server hosting the Health Monitoring application:

- A SOA interface for specific service requests that can be made directly by the Health Service Provider for configuration, data collection, sensor management, and communications with the Patient.
- An Event interface based on the Publish-Subscribe model extended with Context Awareness that allows events to be flexibly published and subscribed between the PHMS and HSP through the mediation of the Message Broker. Events convey both data and context information. A Surveillance Portal can also receive all events and raise alerts.

The PHMS is customized and belongs to one patient. It is the conduit of information between the HSPs and the Patient. The PHMS architecture minimizes sensor-smartphone and smartphone-server communication with local intelligence in the sensor (for normal conditions) and smartphone (for alarm conditions). Each sensor has a 2GB SD memory card to hold up to 1 week of data if the smartphone is unavailable. Smartphones with 500MHz CPU and 64MB RAM are capable for our scenario.

**Health Service Provider**

The HSP hosts a Health Monitoring Server that also supports the 2 interfaces: a SOA interface and a Publish-Subscribe Event interface. It may also include a Complex Event Processing (CEP) engine (not shown in the diagram) for event filtering, correlation, aggregation. There is one such server per HSP (hospital, community health center, family doctor, ambulance, care giver).

Note that a minimal HSP is also possible, to support, for example, a caregiver with a cell phone. In that case, there would not be a Health Monitoring Server or CEP. The cell phone would simple have the capability to subscribe to events relayed through the Message Broker (e.g. by receiving SMS alerts).

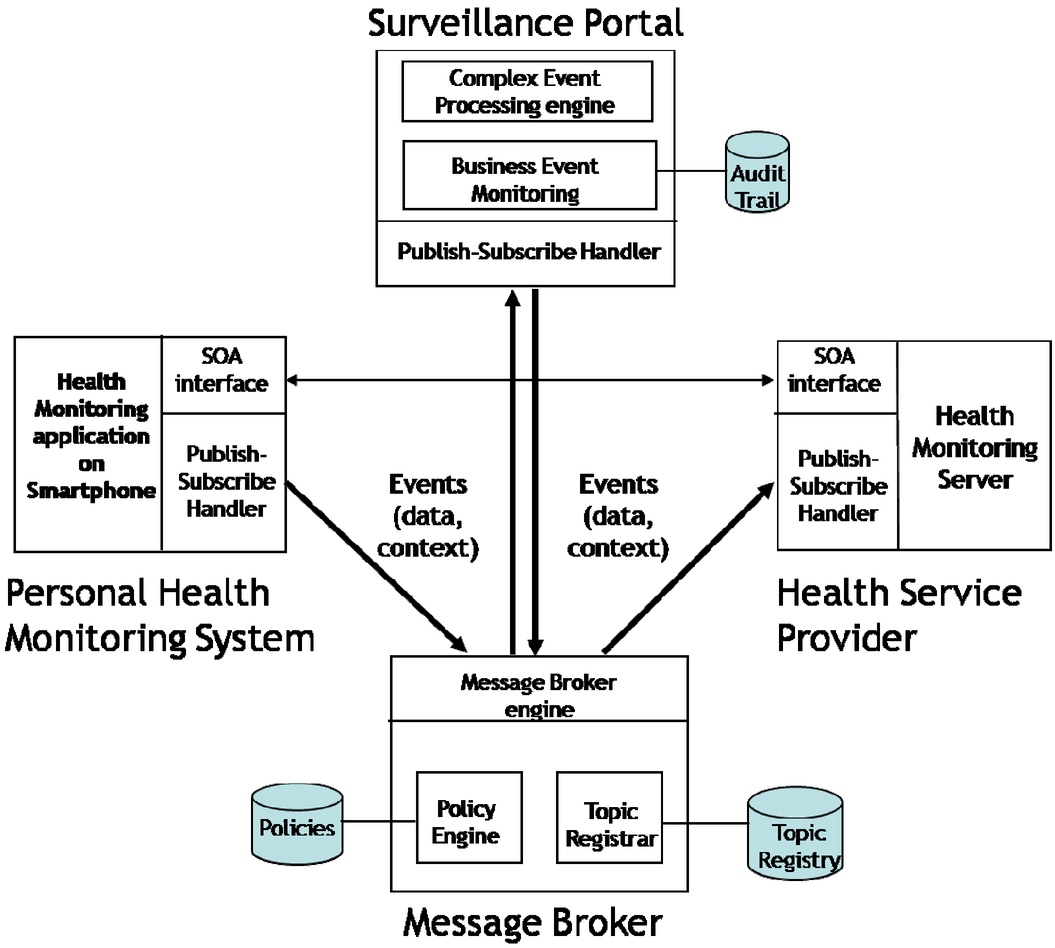


**Fig. 3. System Architecture**

**Infrastructure: Message Broker and Surveillance Portal**

The Message Broker is in charge of routing events from publishers (e.g. the PHMS) to Subscribers (HSPs, Surveillance Portal) based on topics, contents, and context. The Surveillance Portal is in charge of business performance monitoring and management.

The Message Broker and Surveillance Portal could belong to separate organizations or belong to a single integrating administrative entity, like the local LHIN in our scenario, for instance.

**Scenario Analysis**

Events and Alarms are generated by the PHMS. They arrive at the Message Broker which routes them to the relevant HSPs based on policies set up by the HSPs themselves and the LHIN. These events contain both medical data and context information (patient location, patient activities leading to heart attack, medication taking history, whether caregiver is around, current activity). One of the policies may be to automatically forward a selected subset of events to the patient's family doctor in order to keep him/her fully briefed. The location context information provided by the PST makes it possible for the emergency response HSP to select the closest ambulance.

The Surveillance Portal is in charge of integrated business performance management. For example, the Service Accountability Agreement for the LHIN might state that a STEMI heart condition should be processed within 90 minutes, broken down as follows: 30 minutes from alarm to ambulance arrival, 30 minutes for diagnosis of STEMI and patient transport to Heart Institute, followed by 30 minutes for the angioplasty operation. The Surveillance Portal, with complex event processing technology and context awareness, can monitor that this target has been met and report any deviation to the LHIN as well as potentially raised alerts as events that can be subscribed to.

**System Architecture Benefits**

An event-driven architecture brings the following benefits to the HSP:

- The interoperability is lightweight, with loose coupling between information systems. Events are broadcast to whoever is interested in them and authorized to get them. Therefore, the implementation of such architectural approach can be quick, fairly cheap, and can be done independently of the deployment of centralized Electronic Health Records.

- The required building blocks for such an architecture are already commercially available from the major IT vendors, and have been in use for a while in other industries. They are well proven.
- The interface to existing information systems is done via event adaptors which are usually straightforward to develop.

For these reasons, such an architecture is being adopted in healthcare, especially in health monitoring applications. We are also proposing to fully leverage this event-driven architecture with context awareness and complex event processing, in order to take advantage of the functionalities provided by the PHMS.

*C. Policy-based Data Integration*

Our framework views a healthcare network as a streaming database of events in which publishers producing events while subscribers subscribe to them [25]. The Message Broker handles the routing of data streams from source to destinations. The Surveillance Portal can analyze, report and audit streaming data.

When a notification message is received by the policy-based Message Broker, the sender is authenticated similarly. It is then processed by a policy engine based on the policies in the policy database. Figure 4 shows the processing steps for a message.

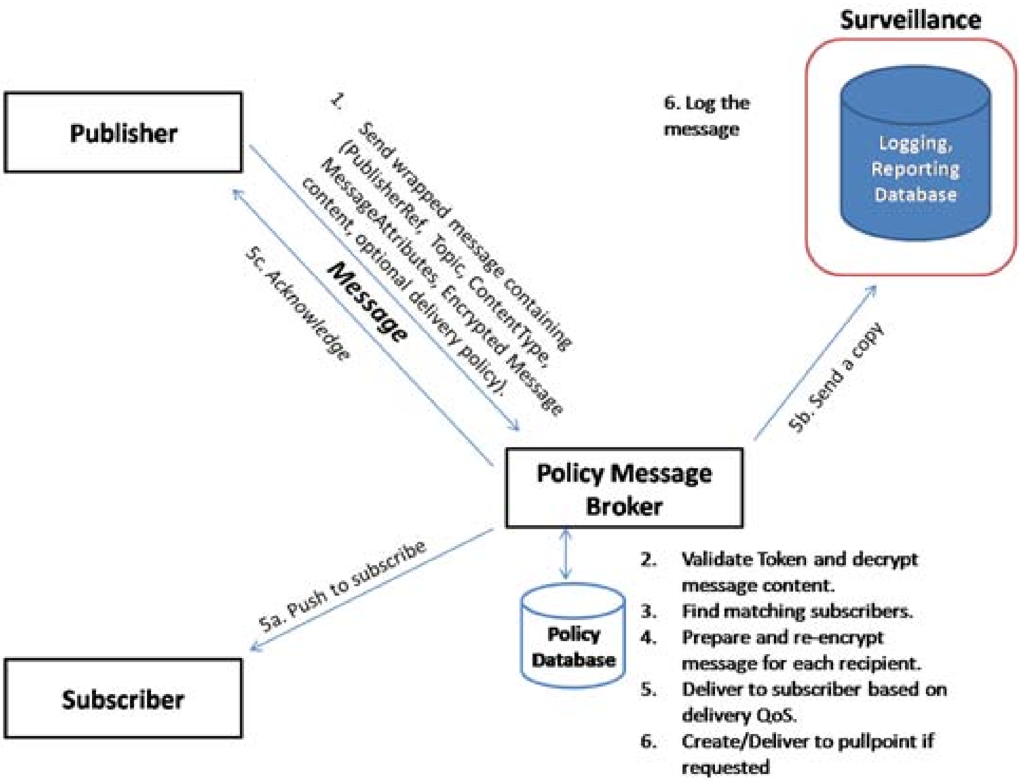


**Figure 4 Message Processing by Message Broker**

**Scenario Analysis**

The Message Broker could contain policy rules about who should receive events (for example, the patient's Family Doctor and the Caregiver), in addition to HSPs like the Health Monitoring Center and the hospital. It can also contain policies about the level of details included in event messages. Different subscribers might receive a different level of detail.

**System Architecture Benefits**

The key characteristics of our scenario are that the processing is event-driven and reactive, and that the configuration and availability of resources is dynamic and continuously changing. Policy-based publish/subscribe enables information to be flexibly defined at run time through the definition of event topics that users can publish or subscribe to. Aggregation and transformation of data can also be defined in the policies controlling subscriptions to events. Information discovery, management and surveillance support are all driven by the creation of declarative policies. The result is a flexible coupling between the PHMS and the HSPs that provides complete support for a full spectrum of interaction patterns, data formats, and delivery modes that can be managed to an expected delivery service quality. An example of such run-time flexibility in the Scenario is the following: if the Patient was driving in the Province of Quebec (which is a different health administration domain than Ontario) when he had the heart attack, events will also be automatically forwarded to the Quebec HSP who will then contact the Ontario HSP for coordination. This configuration is set up with Policy rules in the Message Broker.

### *D. Complex Event Processing (CEP)*

The traditional event correlation engines (Event-Condition-Action model) are not sufficient for Health Monitoring because the events themselves, and their relationships, are much more complex. We need to detect event patterns and associations over time [28]; we need to do event clustering/classification on the fly; and we need to correlate event data with the patient's context.

**CEP engine on the Surveillance Portal and Health Monitoring Server**

We are leveraging ESPER [29], an open source CEP engine with an SQL-like event processing language. It is based on database management techniques applied to event streams. Event queries or rules are stored in the event processor and used for filtering, aggregating, and analyzing incoming business events. We are extending ESPER for data stream mining to support event analysis, association and inference done across time, locations, and sensor types. We are also extending ESPER with context awareness.

**Scenario Analysis**

Based on the Patient medical data and context information (location and current activity, i.e. driving) being sent in events, the CEP engine in the Health Monitoring Server for the HSP automatically keeps tracking the Patient's location until his car is parked. It is also used to identify and propose to contact the nearest ambulance, as well as recognizing the need to configure the patient's smartphone in auto-answer/hands-free mode.

### *E. Context Awareness*

Context awareness can be integrated into the architecture in a number of components and leveraged in order to address this scenario.

**Overview of Context Awareness**

The wearable, on-body or fixed sensors are capable of collecting context information such as: time, the location of the Patient (collected by the smartphone's GPS and embedded RFID tag), the Patient's position (standing up, sitting, laying down, falling), the activity the Patient is currently engaged in (walking, exercising, driving, taking medication, sleeping), the people with whom he/she is interacting or who are nearby (especially, the caregiver), the artifacts he/she is using (like a car), and environment parameters such as temperature, and atmospheric pressure.

This context information in PHMS and the HSP is typically used for [26]:

- Optimized execution of measurements by the sensors: change heart monitoring parameters when patient is exercising
- Decision support
- Presentation of information and services to the Patient
- Service coordination between the HSPs

**Context Awareness Management functions in PHMS and HSPs**

A CEP can be included in the PHMS and in the Health Monitoring server at the HSPs to handle context monitoring, filtering, aggregation, inference using machine learning techniques, and modeling (during the training phase).

**Context-aware Message Broker**

The publish/subscribe model used by the Message Broker is extended for context awareness [27]. In traditional message brokers, the processing of context information is left to the application. However, the policy-based MessageBbroker could use context information in its policies for more efficient brokering, routing, matching of events, thus increasing the scalability and flexibility offered to applications

We are using policies to extend the Message Broker with notions of location, time, activity, and other context information which can be included as additional attributes in the event structure. Publishers can control the broadcast of events by specifying that an event is meaningful only in a certain context; similarly, Subscribers can communicate their interest in events happening only in a specified context (location, for instance).

**Scenario Analysis**

In the scenario, knowing the patient's current location, current activity (driving), as well as knowing if the caregiver is nearby, helps the HSP in evaluating the situation, and assessing the best course of action. The context information is also used in coordinating with the Ambulance and the Heart Research Institute. Finally, it's used in the Surveillance Portal to analyze the compliance with the service accountability agreement.

## V. Evaluation and Discussion

Our scenario illustrates some key requirements for integrating and managing next generation health monitoring systems:

- **Data to Event Processing:** Provide flexible and intelligent configuration and translation of continuous data streams from monitoring sensors into an audit trail of meaningful, context specific events.
- **Event Filtering and Distribution:** Provide context-aware, policy-based dynamic filtering and distribution of events across an entire network of HSPs.
- **Event Monitoring and Alerting:** Provide near real-time monitoring of events and context-aware alerting to facilitate responsiveness and coordination across the entire network of HSPs.
- **Performance Management:** Provide aggregate performance management analysis and reporting from the event audit trail integrated across the entire network of HSPs.

There are a number of existing projects that are piloting next-generation health system monitoring in clinical trials [4, 6, 8, 9, and18]. However, the typical architecture for these projects uses an application specific architecture in which specific sensors are configured to deliver a continuous data stream to a dedicated application server. Integration with existing e-health infrastructure is on an ad-hoc basis in which only select HSPs have accessibility to the dedicated application server, and the integration is manual or batch based.

The table below summarizes and compares the main features of our architecture with the typical architecture that is seen in other projects. The last four entries in the table are specific to the requirements listed above.

TABLE I: FEATURE COMPARISON

| Feature | Typical Architecture | Proposed Architecture |
|---|---|---|
| System Components | Application specific sensors, devices and data collection. Single application server. | Flexibly configured sensors. Smartphone base station. Pub/Sub message broker, Surveillance portal |
| Context Awareness | No | Yes |
| Personal Health System | Holter monitoring system, with off-line data analysis | Sensors and smartphone, with on-line data analysis |
| Dynamic Reconfiguration devices/sensors | No | Yes |
| Data Integration | Selected providers have manual or batch interaction with server. | Flexible, policy-based, context-aware, event publish/subscribe across electronic health network |
| Data to Event Processing | Single application server | Base station primarily, as well as sensors, surveillance & provider server network |
| Event Filtering & Distribution | Application server with manual and/or batch interfaces | Base station filters sensors. Message broker for policy-based event distribution. |
| Event Monitoring and Alerting | Application server with manual & batch interfaces | Context aware at base station, any provider. Policy-based compliance at surveillance portal. |
| Performance Management | Application specific at server. | Integrated network audit trail analyzed and reported at surveillance portal. |
| Security | Ad hoc nature of manual / batch interfaces means that security is handled on a case by case basis. | Online data integration is more available to other organizations, and centralized coordination makes a systematic approach to security more feasible |

By comparison our approach integrates health monitoring systems into an entire HSP network by transforming continuous sensor data into a context-aware event-based audit trail accessible through a policy-based message broker in a flexible, but secure publish and subscribe framework.

## VI. FUTURE WORK AND CONCLUSIONS

We have presented an architecture for data integration of next-generation, context-aware, event-driven personal health monitoring systems based on the use of wireless sensors, smartphones, and data stream mining techniques. This architecture enables significant responsiveness and process optimization by integrating complex event processing that leverages context awareness. Such lightweight event-driven integration for health monitoring can be done quickly, at minimum cost, and does not depend on a formalized electronic health record (EHR).

Our project is at an early stage, and significant work remains in order to perform trials with pilot applications based on this architecture to fully validate the approach. Besides the work on data integration, we are also working on a new set of algorithms for personalized, adaptive and predictive health monitoring for cardio-vascular diseases.

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