MMBIP: Biofeedback System Design on Cloud-Oriented Architecture

Mohammed F. Alhamid[1,2], Mohamad Eid[3], Abdulrhman Alshareef[1,4], and Abdulmotaleb El Saddik
[1]Multimedia Communications Research Laboratory (MCRlab)
[1]School of Electrical Engineering and Computer Science - University of Ottawa
[2] College of Computer and Information Sciences (CCIS) - King Saud University
[3] Division of Engineering, NYUAD, United Arab Emirates
[4] Information System Department, FCIT, King Abdulaziz University
{malha016@, meid@site., aalsh011, elsaddik@}uottawa.ca

***Abstract*— in this paper, we propose a biofeedback system that employs a Cloud-Oriented Architecture (COA) for the dissemination of biofeedback information and services. The architecture provides the software infrastructure to build biofeedback applications that maintain the user's well-being by monitoring a number of physiological parameters and generate the appropriate feedback. Consequently, the architecture combines the collection of various sensory physiological data and utilizes the existing cloud of resources to provide processing, storage, and responses for biofeedback applications. The performance evaluation has shown three distinguished features of the proposed architecture, namely adaptability for various sensory streams, soft real-timeliness, and scalability.**

Keywords- cloud computing, biofeedback, web services.

I. INTRODUCTION

Biofeedback is the science by which the physiological and psychological states of an individual's are measured and presented to that individual, with the objective of training people to improve their health [1]. Biofeedback sensory devices are attached to the user's body, measuring certain parameters such as brain activity, blood pressure, heart rate, muscle activity, then presented to the user via a display interface (such as visual or auditory). By viewing these parameters, the subject can self-regulate various physiological functions and manipulate them at will to improve physiological and psychological performance. Biofeedback is known to support treatment for a wide variety of illnesses including headache and migraine [2], cardiovascular disorders, hypertension, anxiety and duodenal ulcers [3], stutters [4], panic attacks [5], asthmatic conditions [6], hyperventilation syndrome, and sleep apnea [7], post-traumatic stress disorder [8] and can also be of assistance in pain management [1].

A generic biofeedback system architecture is shown in Figure 1. The architecture comprises three components: the biofeedback sensory network cloud, the biofeedback server cloud, and the biofeedback display and response. The biofeedback sensory cloud is composed of biofeedback sensors attached to the human body; it measures various physiological functions and transmits the collected signals to the biofeedback cloud server via a smart device. The biofeedback cloud server performs an in-depth analysis of the collected data and provides storage and dissemination capabilities to deliver the information to the consumer (user, medical staff, research staff, etc.). The biofeedback display/response component provides the means to display the retrieved information in a meaningful way to the consumer.

One of the major requirements for the widespread use of the biofeedback system is its ability to provide distributed and uniform access to heterogeneous biofeedback sensory networks and data. The system should enable any end device (PC, smartphone, etc.) to access biofeedback cloud services and data queried from any sensory network or device independently from implementation. Another requirement is the demand for huge storage and processing power for biofeedback system (due to high volumes of biofeedback data capturing and processing). Finally, data security and privacy are key concerns for the social acceptance and deployment of biofeedback systems; these concerns, however, are not considered in this paper.

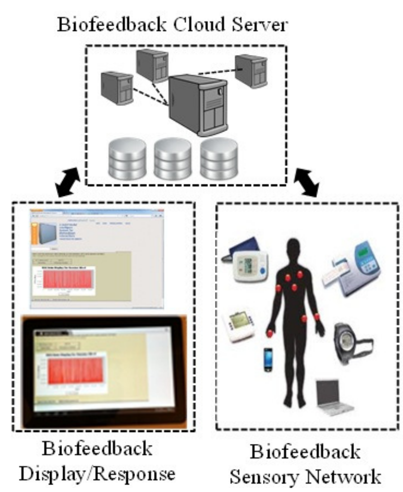

Figure 1: Biofeedback system overview.

To meet these requirements, we propose to use a Cloud-Oriented Architecture (COA) to accommodate for scalability and cope with high resources demand of the biofeedback cloud networks (shown in Figure 1) and to enhance accessibility of the huge repository of biofeedback resources (data and/or

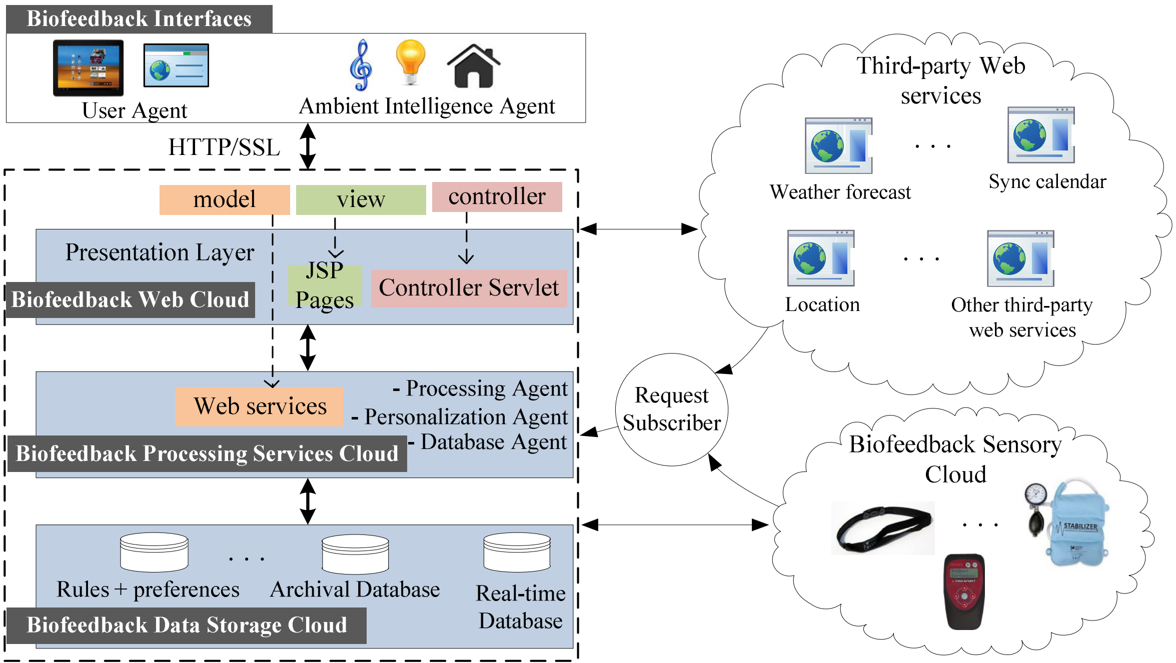

Figure 2: Model View Controller (MVC) on multitier Service Oriented Biofeedback System Architecture.

devices). The cloud computing architecture is a leading architectural practice with several benefits including scalability, abstraction, interoperability, robust connectivity to legacy system, and reduced cost of development and increased maintainability [9].

This paper proposes developing a cloud-oriented architecture that provides access to different types of biofeedback information, manages biofeedback sensory networks, and connects them to the display and response applications (consumer's application) and allows users to access them in common formats. The proposed architecture encompasses the development of biofeedback data processing services (such as data filtration and compression), real-time streaming data services, composition of biofeedback services in scientific workflows, and binding biofeedback display applications with real-time and archival data.

II. Related Work

The biofeedback system facilitates the recognition of the user's health condition in order for the users to maintain their well-being. Therefore, the software architecture for such type of systems should be distributed, extendable, scalable, and flexible. In this section, we highlight related software development systems for some comparable applications.

K. Ahmed and M. Gregory [10] proposed a framework for integrating wireless sensor network with cloud computing. The framework includes the data processing unit, publisher and subscriber broker, and data repository. The paper shows the flow of interactions between the framework components in a cloud environment. J.T. Hsu et al. [16] proposed a mobile personal health system based on cloud computing. The system separates the interfaces from the implementation, allowing them to be implemented as a set of provided services. The paper focuses on the application and platform layers.

The web services play an important role in facilitating the exchange of data in such cloud-oriented architecture systems. For instance, E. Dalsgaard et al. [11] address in their work the problem of integrating health information across many healthcare providers using web services. S.-H. Liu et al. [12] also address the problem of heterogeneous data and multimedia health-related contents. A system was designed to help in building a large-scale multimedia database that can be accessible by different clinical platforms. Using semantic and service ontology along with the help of annotations, they were able to discover and update specific data. Similarly, R. Marker et al. [13] proposed a biomedical question answering system using web services.

There are also a number of research publications about biofeedback systems being proposed to promote treatment, or monitoring. For instance, a biofeedback system was designed by H. Liu el al. [14] to establish a stress free environment on the airplane. A music recommendations system was developed to help reduce travelers' stress levels by playing a list of music favoring the reduction of stress.

III. Proposed Cloud-Oriented Biofeedback Architecture

A cloud-oriented architecture approach for biofeedback systems is proposed as shown in Figure 2. The core of the proposed solution is the composition of three clouds: the Biofeedback Web Cloud, the Biofeedback Processing Services Cloud, and the Biofeedback Data Storage Cloud. Interactions with third party web services cloud as well as the biofeedback sensory networks, and the biofeedback interfaces complete the proposed architecture.

A. *Biofeedback Interfaces*

The biofeedback interfaces host interfacing agents that are responsible for interactions between the biofeedback system and the ambient environment and the user. For example, the physiological state of the user is presented to the subject or a third party user (such as a family member or a medical staff member) using the user interface component. Eventually, the user adapts their living style according to the presented information with the objective to promote well-being. Furthermore, the biofeedback system controls the ambient environment using the ambient intelligence interface. In this case, the biofeedback system can tune the ambient environment settings (light intensity, music, home appliances, etc.) in order to provide a healthier environment that promotes well-being.

B. *Biofeedback Web Cloud*

The biofeedback web cloud handles all the Hypertext Transfer Protocol (HTTP) requests, where it is responsible for carrying communications between the client interfaces and the biofeedback processing logic cloud. Specifically, the cloud manages the interactions between the client interfaces and the biofeedback processing logic cloud by translating all the HTTP Put and Get into a form that can be processed by the biofeedback processing services. It also sends the results back to the requestor by implementing various data representation methods such as graphs and tables.

C. *Biofeedback Processing Services*

The biofeedback processing services cloud is composed of services that perform signal processing and conditioning onto the raw data collected from the biofeedback sensory network. Examples of signal conditioning include filtration, re-sampling, amplification, and isolation and scaling. Signal processing, on the other hand, involves data compression or decompression, signal analysis (such as computing the heart rate from an electrocardiogram (ECG) signal, or the average skin temperature over time). Note that multiple web services can be composed to provide a more complicated processing and/or analysis.

One important processing service is the data stream processing service that is associated with observations collected from various sources (biofeedback devices). The streaming service can be either online (when the user is currently using the device and sending information to the servers cloud) or offline (when the user is disconnected from the server and previous sessions need to be observed).

D. *Biofeedback Data Storage*

The biofeedback data storage cloud hosts various biofeedback databases and servers. Three classes of databases are identified: real-time database, archival database, and personalization database. The real-time database stores data sent by online subjects (currently connected to the server) where the data can be relayed to a client via a streaming service for soft real-time monitoring. The real-time data is copied from the real-time database, filtered, compressed, and stored in the archival database (compression is needed as biofeedback systems comprise huge volumes of data). The archival database is used to store historical data collected from previous sessions with users. Finally, the personalization database stores user preferences and personalized rules for the biofeedback system settings. For instance, user preferences about the media of communication (auditory, visual, etc.) or relaxation exercising preferences are stored in the personalization database.

IV. Case Study: Software Implementation of a Multi-Modal Biofeedback Interactions Prototype (MMBIP)

In this section, we present a case study to demonstrate building a biofeedback prototype using the proposed architecture of Figure 2. The biofeedback application uses an interactive mirror to interface various physiological parameters with the subject (or a third party). The application details can be found in one of our earlier work [15]. The objective of the application is to promote well-being of the users by incorporating different biofeedback responses in an Ambient Intelligent (AmI) environment.

A. *Implementation Details*

The implementation is separated into two phases as shown in Figure 3: The "capture" phase that captures various physiological sensory data and transmits it to a the database cloud for storage and further analysis, and the "retrieval" phase where the data stored in the database cloud is delivered and displayed to the end users in an interactive manner via a web browser. Figure 4 shows how the service communication is broadcast between the data collection interfaces and the biofeedback services during the capture phase.

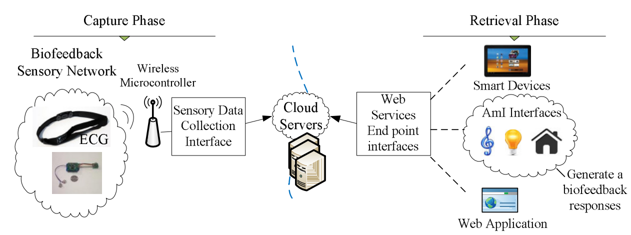

Figure 3: Capture and retrieval phases in the biofeedback prototype.

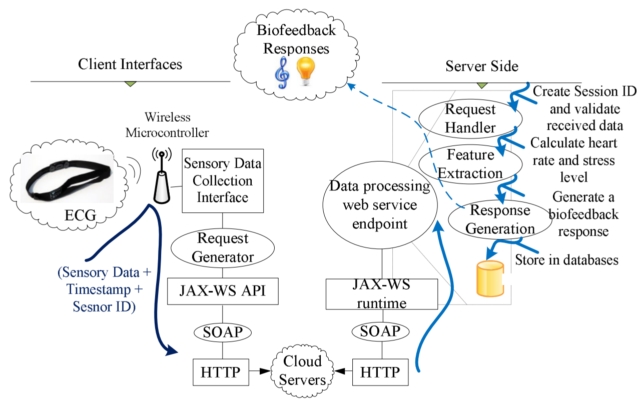

Figure 4: Web services cloud communications in the biofeedback system prototype.

In Figures 3 and 4, the client interfaces represent all the devices that either sense physiological parameters or acquire them. For instance, we used an Arduino Wireless Protoshiled microcontroller to establish the communication between the biofeedback sensors and the web services cloud. At the same time, a Samsung Galaxy Tab 10.1 was used to acquire a biofeedback service such as browsing the collected sensory data. Hence, these devices communicate with the biofeedback sensors which then collect the sensory biomedical data or handle the sensors data streaming. For the MMBIP prototype, the communication between the biofeedback sensors and the data collection interfaces can be carried by Bluetooth or Wi-Fi and then uploaded using web services to the server cloud for further processing and response analysis.

In the MMBIP prototype, we also used the T31 Polar belt [18] to record the heart peak signal. The device can send up to 250 samples per second which has been used to calculate the number of peaks (heart rate) and to measure the R-R intervals in order to determine the levels of stress. The system determines high level of stress if the Coefficient of Variations of R-R Intervals (CVRR) has a lower value, where the higher value of CVRR determines that the user is more relaxed. Figure 5 shows a screenshot of the ECG signal recorded in one of the sessions. The X axis in the ECG diagram represents a unit of time in milliseconds, while the Y axis represents the digital representation of the recorded heart signal. To clarify the presentation of the ECG graph, we showed only 25 seconds of the original ECG peak detected signal.

The server side components contain a number of web services endpoints and include: (i) a data processing web service; (ii) a biofeedback service catalog; (iii) a user login web service; (iv) a user registration web service; and (v) third party web services. The functional details of the most important web services are described in the rest of this section.

Data Processing Web Service: In our scenario, we mentioned that the ECG belt, for example, is streaming the heart signal to the server by calling JAX-WS APIs to reach the services at the server cloud side. The data processing web service has a number of methods to handle the client requests. Once the data is received from the biofeedback client interfaces, the data processing web service calls all the required database agents to store the data into the real-time database cloud in order to serve all the client interfaces who desire to have a real-time access to them. It also alerts other database agents who store a copy of the data stream in the archival database for offline data display and manipulation. The data processing web service calls supportive classes to run the biofeedback data analysis and feature extractions.

Biofeedback Service Catalog Web Service: This catalog exposes all the available biofeedback services contributed by the biofeedback server side. More specifically, by using this web service, the client can query the list of all available biofeedback services which can be categorized as: physiological measurements, weight monitoring, event tracking, weather, ambient temperature, and others. It is also possible to query all the services and biofeedback sensors that belong to a selected category.

B. *Static and Dynamic System Visualization*

The static view of the system is presented in a UML class diagram in Figure 6. The presented classes are the main object types to mention. Each user has a set of assigned sensors that he/she can interact with. A user can have one or more recorded sessions. Sessions can have multiple streams, where each stream carries the data being published by a single sensor. Biofeedback system designers need to extract different parameters from the collected biomedical signals. Therefore, we included an interface named Feature to fit their own signal processing needs.

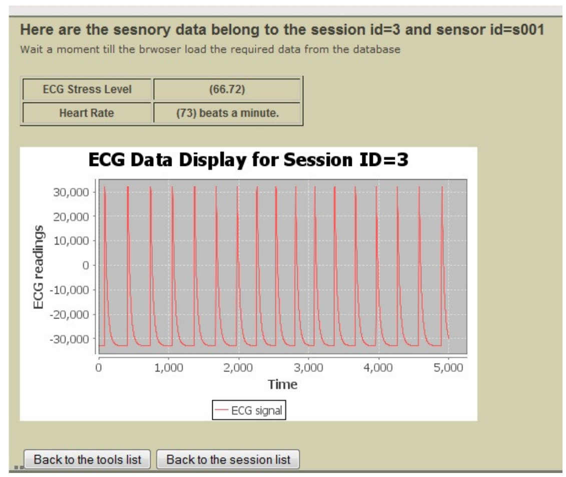

Figure 5: A screenshot of the prototype implementation of acquiring the ECG readings for one of the stored sessions. It shows the ECG peak detected signal together with the heart rate and stress level.

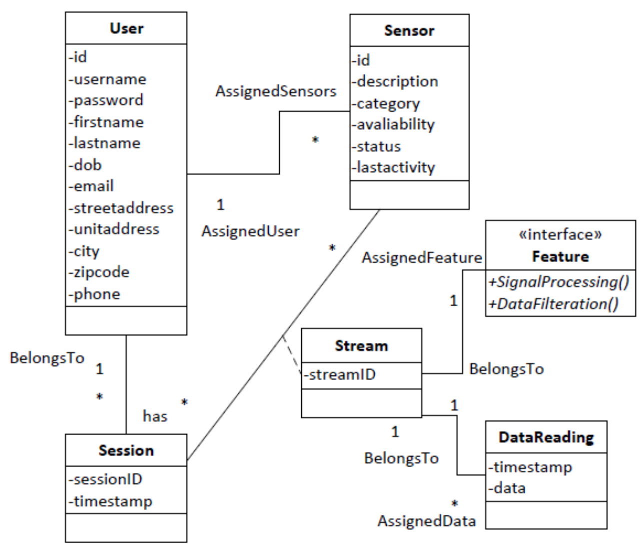

Figure 6: Class Diagram specifying the static structure of the implemented biofeedback system prototype.

The dynamic view of the system is presented in UML state chart diagrams as shown in Figure 7 and 8. The figures help to demonstrate how the biofeedback entities are interacting with the system by describing their activity behavior. On one hand, Figure 7 describes the user browsing behavior to query a variety of biofeedback services. The successful user scenario starts by successfully being authenticated to the server. Then, the user can follow various query activities by browsing the list of available sensors and related recorded data sessions. On the other hand, Figure 8 describes different activity behaviors that the biofeedback device can initiate after being registered to the server. The “Online” and “Offline” presents the device connectivity status to the server. The two states - passive publishing and active publishing - describe the behavior of the device, either from simply recording the sensory data, or streaming them to the server cloud; only when it is necessary does the state change to “active publishing”. These two states can enable the sensors to conserve bandwidth and battery by sending only valuable information to the server cloud for analysis.

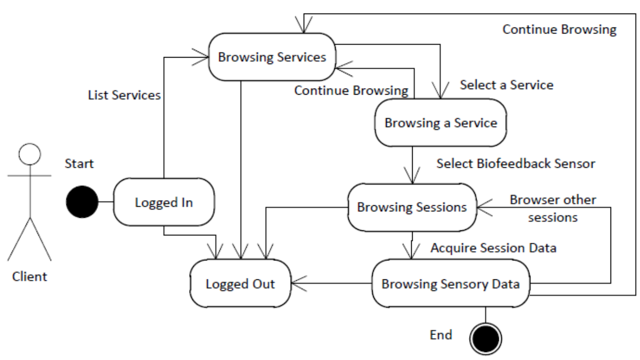

Figure 7: The dynamic behavior of the client to browse biofeedback services.

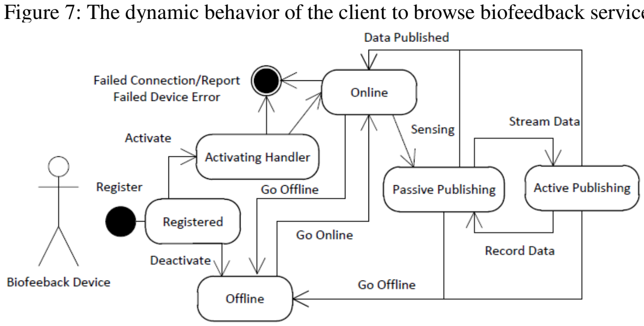

Figure 8: The dynamic behavior of the biofeedback device workflow activities.

V. Evaluation and Testing

The adaptability and performance evaluations aim at validating the operation and testing of the proposed architecture. The system functionality is tested using a JUnit framework 4.1.10 [17]. Nine testing classes were created, each with a number of test methods. These methods include testing the web services by posting different invalid arguments and by matching expected results.

A. *Adaptability Evaluations*

Adaptability refers to the ability of the architecture to support the acquisition and dissemination of biofeedback sensory streams at various sampling frequencies. In this study, we include three types of streams: high frequency (HF) stream (250 Hz), intermediate frequency (IF) stream (20 Hz), and low frequency (LF) stream (2 Hz). The experiments have been done within the university’s network and using a cloud of two servers and three parallel client machines each with 100 threads.

We measure the overall response time in two separate scenarios: (1) when a biofeedback device pushes data to the server and saves it into a database cloud (named the capture time), and (2) when a viewer (consumer) requests the data from any web client and retrieves the data from the database cloud (named retrieval time). Furthermore, three classes of biofeedback data retrieval are experimented with: high frequency (HF) data of 250 Hz (ECG signal), medium frequency (MF) of 20 Hz (accelerometer), and a low frequency (LF) data of 2 Hz (human skin temperature).

The results of the experiment are presented in Table I. The values shown in Table 1 are averages of 100 trials. Note that the capture delay is negligible compared to the retrieval delay. For instance, the HF overall delay is 1.49 seconds, which is acceptable for soft real-time performance.

TABLE I. Experimental results for measuring the response time for capturing and retrieving biofeedback data in three classes: high frequency, medium frequency, and low frequency.

	Capture Time		Retrieval Time	
	Avg	**Std**	**Avg**	**Std**
HF (250 Hz)*1	0.22 ms	0.09	1.49 s	0.35
MF (20 Hz)*2	0.03 ms	0.001	0.24 s	0.12
LF(2Hz)*3	0.09 ms	0.003	0.09 s	0.01

*1: High Frequency, *2: Medium Frequency,*3: Low Frequency, ms: Milliseconds, s: seconds.

B. *Real-timeliness Evaluations*

Real-timeliness measures the ability of the proposed architecture to support real-time streaming of biofeedback sensory information. Two response parameters are considered: the total response latency and the total response jitter. The total response latency is defined as the summation of the capture delay and the retrieval delay. Furthermore, the response jitter represents the maximum variations in the total response latency. Both are measured in milliseconds.

In Table II, we plot the request rate (requests per second: 10 clients, 50 clients, 100 clients) versus the response time ranges in milliseconds for each resource in the cloud. It shows the client request completion over experimental trials for the three types of streams: HF, MF, and LF. Except for minor disturbances due to network traffic condition, the retrieval delay is always bound by a value less than 2 seconds for high frequency streams. Therefore, the proposed architecture for biofeedback system performs in soft real-time.

TABLE II. Retrieval time of the biofeedback data in three classes: high frequency, medium frequency, and low frequency.

	<100 ms	<200 ms	<300 ms	<400 ms	<500 ms	<1000 ms	>=1000 ms
HF*1 10C.	0.00%	0.00%	0.00%	0.00%	0.00%	55.00%	45.00%
HF 50C.	0.00%	0.00%	0.00%	0.00%	0.00%	23.33%	76.67%
HF 100C	0.00%	0.00%	0.00%	0.00%	0.00%	10.91%	89.09%
MF*2 10C.	0.00%	40.00%	50.00%	10.00%	0.00%	0.00%	0.00%
MF 50C.	0.00%	12.33%	16.67%	11.00%	16.67%	43.33%	0.00%

	<100 ms	<200 ms	<300 ms	<400 ms	<500 ms	<1000 ms	>=1000 ms
MF 100C	0.00%	6.77%	8.47%	5.08%	8.48%	28.83%	42.37%
LF*3 10C.	90.00%	10.00%	0.00%	0.00%	0.00%	0.00%	0.00%
LF 50C.	30.00%	40.00%	30.00%	0.00%	0.00%	0.00%	0.00%
LF 100C	15.25%	45.16%	20.34%	13.56%	5.69%	0.00%	0.00%

*1: High Frequency, *2: Medium Frequency,*3: Low Frequency, ms: Milliseconds, C: Simultaneous connections.

Figure 9 shows the total response latency and jitter versus the number of clients simultaneously accessing the biofeedback system. The plotted values are the averages for HF, MF, and LF streams. The graph demonstrates the average delay is maintained within 250 milliseconds.

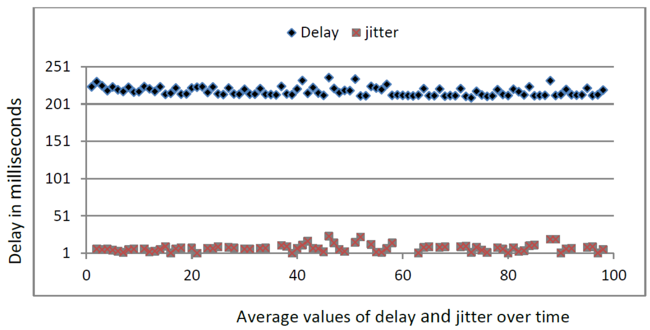

Figure 9: Total average real-time performance for the total system latency.

VI. Conclusion

This paper proposes a biofeedback system based on a cloud-oriented architecture that can be used to self-moderate several physiological functions in order improve performance and maintain self-well-being. As shown in the performance evaluation, the distinguished features of the proposed architecture are: adaptability for various sensory streams, soft real-timeliness, and scalability. Furthermore, the cloud-oriented approach facilitates distributing biofeedback services and concurrent access to heterogeneous biofeedback sensory networks and data in soft real-time fashion.

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