LIVE BIO-SENSOR NODES FOR INVISIBLE PERVASIVE COMPUTING

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Abstract

The focal point of this paper pivots on a most plausible proposition to develop a model via which live biological entities can be visualized as components of a wireless sensor network. Inherent distributed communication methodologies present among such chosen organisms are exploited to provide the interaction mechanism between the nodes of the sensor network. The related functional specifications of the bio-sensors and their related rationale have been discussed. The sensor network thus developed is used as a tool for implementing Pervasive Computing. Salient benefits of using Bio-sensor nodes over electronic sensors have been discussed.

I. Introduction

The development of a model aims at building a mock instance of reality. Our efforts delve on building a model to encompass living entities to allow for the construction of a sensor network. Such sensor networks are the very basic tools to implement Pervasive Computing (PerCom). The sensor nodes in these networks gather and process data and pass them on to the more capable or intelligent nodes. They are embedded with the ability to take intelligent decisions after reviewing the inputs which they have received. It is this plethora of data and the significant abilities of the network nodes to filter and process it which allows for the creation of an intelligent ambience. This is what PerCom aims to achieve. We can leverage this idea of gathering data from various sources in order to provide the levels of ubiquity discussed by Weiser (1991) in his famous reference to "*the vast amounts of information available to us even while leisurely strolling through pristine woods*". An odd irony lies in the fact that even though computing environments have evolved greatly over the last few decades both in terms of processing capabilities and with respect to the plethora of applications they can now handle successfully; the "Human" domain Weiser (1991), Saha and Mukherjee (2003) has more or less remained delineated from this computing environment. PerCom, Saha and Mukherjee (2003), allows for a framework for the integration of the "computing devices" with the "physical

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(biological) space" around users in a way such that these devices themselves become embedded into the fabric of everyday activities. The major point of concentration with respect to PerCom is that unlike as we normally observe the computing environment to be separate from our natural periphery it aims at developing an intelligent ambience, indistinguishable from physical space, which has embedded smart sensors (may be live!) performing information storage, retrieval, and processing, Saha and Mukherjee (2003). Interestingly live organisms already possess the characteristics which we crave for in the electronic sensors implemented in conventional sensor networks. The capability to communicate with similar entities, the ability to react to the environment and most of all the intelligence to manage themselves without the need for supervision during deployment and operation. In short, biosensors can use live organisms such as bacteria and detect them, too. However for this to become feasible it is imperative to be able to interpret the behavior of these bio-nodes either by observation of their direct reactions to the stimuli provided via the environment or by keeping a check on the communication methodologies they exploit in order to maintain their inherent natural balance. Consider that the human body, perhaps the largest and the most complex repository of information ever, is actually a network of trillions of nodes working together in tandem; as expressed by Alan Kay during his keynote speech at the "Congress on the Future of Software Engineering" (http://www.cofes.com/news/?20030122). This internal self-supporting and self-healing network uses biological mechanisms to sense impulses from its current environment and thereby determines the most suitable response to it. The nodes in these large bio-networks are similar in their functionality with respect to the more conventional views we hold when considering macro-scale structures. Bio-sensors such as genetically engineered bacteria have been proven useful because of their ability to "tattle" on the environment. Such commonly used bacteria have been designed in Oak Ridge and Knoxville to give off a detectable signal, such as light, in the presence of a specific pollutant they like to eat. They glow in the presence of toluene, a hazardous compound found in gasoline and other petroleum products. They can indicate whether an underground fuel tank is leaking or whether the site of an oil spill has been cleaned up effectively. These informer bacteria are called bioreporters. In 1990, a bioreporter of naphthalene was developed and tested at the University of Tennessee at Knoxville (UTK), Oak Ridge National Laboratory has been developing biosensors and bioreporters for almost a decade. Carl Gehrs, director of ORNL's Center for Biotechnology, says that ORNL's program in biosensors is "a leader among DOE national labs, which is a best-kept secret." He added that ORNL is proposing to develop biosensors that can detect the presence of biological and chemical warfare agents for military use and for determining the effectiveness of cleaning up waste sites. Another major rationale for developing sensor networks embedded with bio-sensor nodes apart from the inherent distributed communication mechanisms they already possess is **Cost**. A small Bluetooth radio costs about a few US dollars, but even at this rate, to deploy a million (or more so) nodes in a densely packed manner over an area of interest would cost quite a few millions. This motivates us to consider zillions of all-pervasive micro-organisms (present everywhere) as part of an existing "live" pervasive network (PerNet) that requires no effort in terms of deployment and maintenance (Fig.1). Being homogeneous in nature, this live PerNet is by default integrated with the human environment. In a recent study, conducted by the University of Calgary's Department of Microbiology and Infectious Diseases to model the swarming behavior of bacteria, it was learned that bacteria not only swim in solution but also can move over certain surfaces in a swarm. This sparks interest into the *cell-to-cell signaling* involved in swarming.

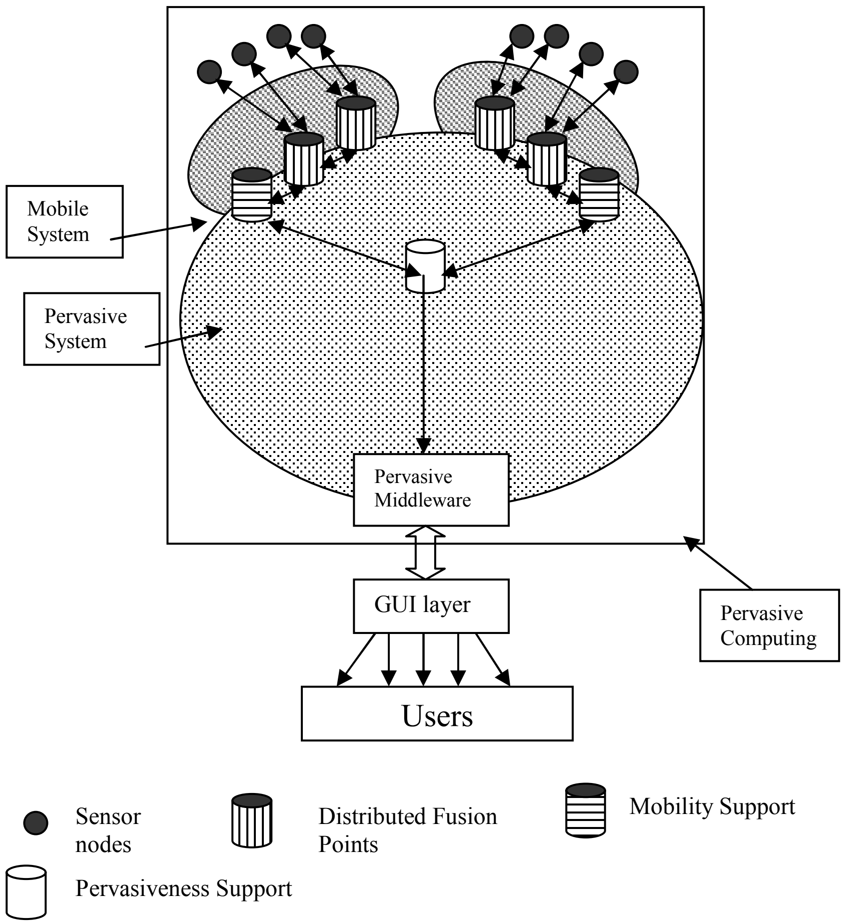

Fig 1. A pervasive sensor network, where data is accumulated only to be preprocessed and passed on to the fusion point from where it is sent via the internet to the end user.

Therefore, a very tiny range wireless communication is already in place. From sensor networking point of view, the only missing link for realizing a PerCom system with these bio-sensors is a mechanism that can control and assimilate information related to the behavioral characteristics of these live organisms, while the processes for information gathering and network management could be hived off to their domain. Our research efforts develop the basic model of the bio-sensor which allows for the inclusion of a living organism as the low-level sensor node in a sensor network. This sensor network is used to gather the needed data for development of the PerCom environment.

II. Black Box Modeling

The range of organisms to be used as the data gathering nodes can range from the smallest bacteria to ants and other live entities. This commmands that the model must accommodate a large variety of organisms as well as provide for the efficient and effective utilization of their individual properties. A live organism can be modelled as an entity in computing fora by understanding the basic functionalities and limitations imposed on those functionalities by nature. In section III we will discuss in detail with reference to a particular organism, its suitability with respect to the model so developed. The sensor nodes will execute certain basic Input Output functions and it is on the basis of these that the capabilities of the bio-sensor nodes are modelled. The Input scenario for a sensor node consists of 1) *Environmental Stimulus* and 2) *Inter Entity Stimulus*. While the Output scenario consists 1) *General Flooding of message* and 2) *Entity Directed query*. Thereby basic functionalities of a live organism modelled as a black box would be to (1) *communicate with the environment* (2) *communicate with similar entities* (3) *respond to changes in environment* (4) *respond to messages received from similar entities*. This is illustrated in Fig. 2.

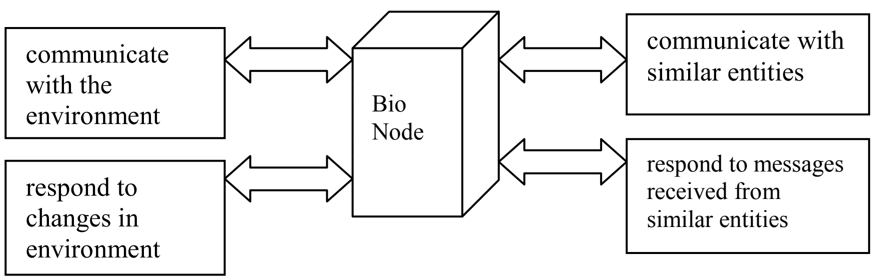

Fig 2. A generic black box model of bio sensor nodes. This entity can perform the four basic interactions (1) communicate with the environment (2) communicate with similar entities (3) respond to changes in environment (4) respond to messages received from similar entities.

To allow for sufficient exploitation of the usage of these entities certain sub-functions must be incorporated in the basic interactions. We analyze the basic functionalities afforded by these entities based on the input output scenarios that they have to undergo.

(1) communicate with the environment

(satisfies **Environmental Stimulus, General Flooding of message and Entity Directed query)**

- *(1a) Probe environment temperature*
- *(1b) Probe environment Pressure*

(1c) Probe environment acidity
(1d) Probe environment nutrition level

(2) communicate with similar entities

(satisfies **General Flooding of message and Entity Directed query)**

(2a) Send message to closest node
(2b) Send message to particular node
(2c) Flood Message

(3) respond to changes in the environment

(satisfies **Environmental Stimulus)**

(3a) Increase metabolism rate
(3b) Increase internal temperature
(3c) Decrease internal temperature
(3d) Decrease metabolism rate
(3e) Specific response

(4) respond to messages received from similar entities

(satisfies **Inter Entity Stimulus)**

(4a) Signal affirmative
(4b) Signal decline

All the basic operations of the organism required for it to function as a basic node are satisfied by the above hierarchical functional classification. An important consideration for extending the functional hierarchy to more than two levels depending on the specific nature of reactive mechanisms employed by the bio-sensor nodes leads to a flexible framework to allow for the integration of organisms possessing specific traits. Multi-level specifications are best suited for accomodating various strains of an organism with very fine differences in their response mechanisms. The main fusion point node at each level in the hierarchy assimilates and interprets information gathered by observing the behavior of these nodes and must relay them in a specific format to the nearest cluster head, this is illustrated in Fig.3. It is through this model that the realization of a sensor network to implement PerCom becomes plausible. Two of the most critical aspects of developing the so called intelligent ambience using this model combined with the sensor network topology are ***Context sensitiveness*** and ***context awareness***, Judd and Steenkiste (2003), Mäntyjärvi et al. (2003), these are an inherent requirement of Pervasive systems and are part of the functionalities exhibited by the live organisms. These nodes respond on their own to changes in their immediate environment and hence the need for supervised operation is eliminated. This is over and above the functionalities offered by these bio-organisms vis-à-vis electronic sensor nodes. Live bio-sensors offer us all the functionalities their non-living counterparts can perform and extend the two basic Pervasiveness critical features of context sensitiveness and awareness for free. The concept of *"More for Free"* is definitely a big draw. These mechanisms perfected over millions of years of evolution are about as reliable if not more than the intelligence embedded in sensor nodes to perform the same activities. The non-living local data assimilators and processors are placed with their accessory electronic paraphernelia at the highest level in the topological hierarchy, i.e. at the cluster head level. This is the only non living portion of the topology. The fusion points may contain the Super-Bio-Sensors, which are the bio-organisms which are superior in terms of their range of functionalities and information processing capabilities. An example of such a hierarchy would be to interpret the behavior of the worker bee at the lowest level wherein its job would be to relay information regarding changes in temperature via its reactive mechanisms, the queen bee at the next highest level and electronic sensors meant to measure their frequency of emitting a particular acoustic signal at the cluster level.

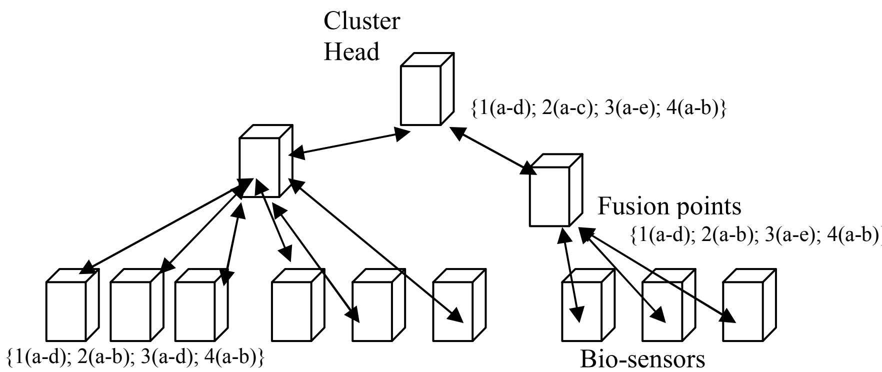

Fig 3. Hierarchical layout of the bio-sensor network. The lowest level nodes have certain functionalities ranging from 1(a-d);2(a-b);3(a-d);4(a-b) while the fusion point nodes have a larger range of interactions 1(a-d);2(a-b);3(a-e);4(a-b) and finally the local cluster head has the following interaction range 1(a-d);2(a-c);3(a-e);4(a-b)

III. Sensor Network Architecture

It is the ultimate aim of our efforts to develop the sensor network based on Bio-nodes to build the PerCom embedded environment. To realize the network we must first give due attention to the conventional sensor nodes that are today employed in traditional sensor systems. Multifunctional sensor nodes that are small in size and can communicate untethered over short distances are the primary building blocks of dense sensor networks. These tiny sensor nodes which consist of sensing, data processing and communicating leverage the idea of sensor networks Akyildiz et al. (2002), Wokoma et al. (2002), Van Dyck and Miller (2001), which are the very basic bedrock of systems satisfying the requirements necessary for PerCom. A sensor network is composed of a large number of sensor nodes that are densely deployed either inside the phenomenon or very close to it. Since the position of sensor nodes need not be engineered or pre-determined, this allows for random deployment in inaccessible terrains or disaster relief operations. On the other hand this also means that the sensor network algorithms and protocols must have the property to re-organize themselves. Another unique feature of sensor nodes is their ability to cooperate among themselves. These features themselves have cleared the way for using biological organisms as the basic units of such data gathering and processing networks. Sensor nodes are fitted with an onboard processor. Instead of sending the raw data for fusion they locally compile summaries from the raw data and send over only those summarized information strings to the fusion point. Again this criterion is more than satisfactorily fulfilled by biological organisms. The above-described features ensure a wide range of application areas for sensor networks such as healthcare, military, home use, and commercial environments. This leads to an all-Pervasive presence of sensors that gather and process huge amounts of information so critical for connecting the human domain with the electronic domain. The sensor network thus formed by the use of such nodes has a three-tier structure. The layered architecture ensures a hierarchical distribution of processing capabilities and functionalities. The very basic nodes at the lowest level are the ones responsible for the data gathering and forwarding to their respective fusion points found in the next higher level. The fusion points at the sensor network level summarize the meaningful information and forward them onto the cluster heads that can actually take intelligent decisions based on the data compiled from these fusion points. The range of functions related to each node in the respective layers is directly proportional to its placement in this hierarchical layout. The lowermost level contains the maximum number of possible communication channels while at each subsequently higher level the number of possible communication channels decrease. This topological separation at each level is absolutely in tandem with the hierarchical classification in biological organisms.

IV. Behavior Interpretation of Bio-sensors

In response to any stimulus injected into the immediate environment of a bio-sensor, a particular or generic response can be identified. This response can differ with respect to the entity we choose to use as the information gatherer of the network that we wish to design. We develop our case based on strains of bacteria, which may be employed to gain information about the immediate conditions of the surrounding environment.

IV a. Quorum Sensing

In recent years it has become apparent that bacteria coordinate their interaction and association with higher organisms by intercellular communication systems. Intercellular communication via diffusible chemical signals is well described for bacteria and functions to modulate a number of cellular processes. The perception and interpretation of these signals enables bacteria to sense their environment, leading to the coordinate expression of genes. The result of this communication is the proper and appropriate response of the bacterial community to its surroundings. Intercellular responses resulting from such signaling include the control of competence, sporulation, and virulence factor production. In gram-negative bacteria, one type of communication system functions via small, diffusible N-acyl homoserine lactone (AHL) Johnson (2000), Bassler (1999), referring to Fig. 4, signal molecules which are utilized by the bacteria to monitor their own population densities in a process known as quorum sensing. Given that a large proportion of the bacteria colonizing the roots of plants is capable of producing N-acyl-L-homoserine lactone (AHL) molecules, that these bacterial pheromones serve as signals for communication between cells of different species is a reliable understanding. Bacteria not only exist as individual cells but also often coordinate their activities and act in a concerted manner similar to that of multicellular organisms. Such interactions require sophisticated cell-cell communication systems to adjust the various functions within a bacterial community. Certain luminescent bacteria that are widespread in oceans but are harmless to people two species, called Vibrio harveyi and Vibrio fischeri, emit a blue glow. These glowing bacteria are capable of perceiving when they are in a dense population. Each bacterium emits a small signaling chemical that builds in concentration as a population grows. When there is enough chemical, the bacteria adjust to their crowded environment. For V. fischeri and V. harveyi, the response is to emit a blue glow. In fact, V. harveyi has two quorum-sensing systems, either of which can trigger the glowing. One system tells the bacteria how many of its own species are in the area; the other tells how many other types of bacteria are around. This is significant as it would allow for the development of Bio-sensors not limited to one species alone but instead to be composed of different species of the chosen entity, giving a more realistic possibility of real life implementation, since in actual conditions some different strains of each organism would definitely be present in the majority population. Bacteria employ a number of different classes of QS signal molecules. The most studied molecules are the *N*-acyl-L-homoserine lactones (such as 3-oxo-C6-HSL below).

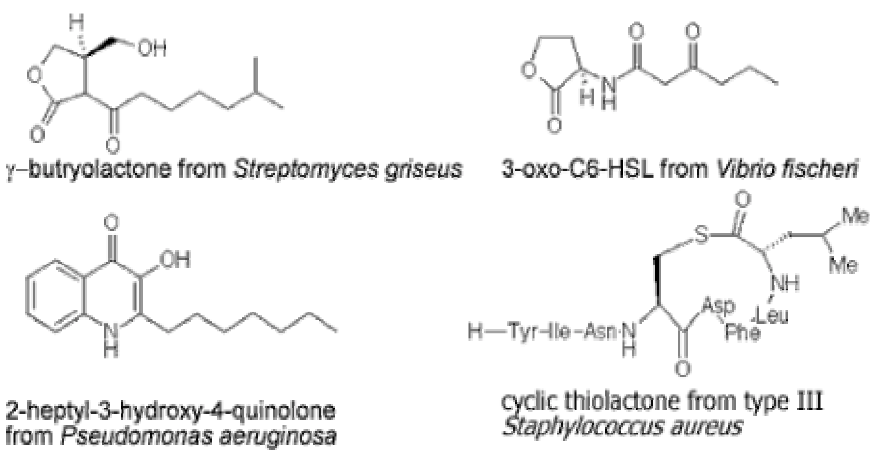

Figure 4. The various molecules used by bacteria during Quorum Sensing

IV b. Airborne intercellular communication

Experiments conducted by R.D. Heal and A.T. Parsons, Heal and Parsons (2002), at BioPhysics Research Group, QinetiQ strongly suggest that an airborne chemical media for the propagation of messaging signals exist between physically separated populations of bacteria. Intercellular signalling between physically discrete populations of E. coli BL21 was analysed in bi-partite Petri dishes. Transfer of a growth-promoting signal resulted in induction of resistance to the antibiotic ampicillin. Optimal expression of the signal occurred when the signalling population was established as a bacterial lawn for 24 h. This represented an entry into the stationary phase of growth, as indicated by the expression profile of the RNA polymerase subunit σ^{38} (σ^{S}; sigma S). The growth-promoting effect was also observed when E. coli DH5a (luxS –) was used as the signalling population. Preventing passage of air between the two populations resulted in a complete cessation of the growth-promoting effect. The chemical Indole has been touted as the possible inducer for this effect.This effect is highly significant in cases where the bio-sensors will be deployed densely, since the efficacy of this mechanism is found to reduce by about 80% when separation distance between the two cultures reaches about 25mm. This mechanism provides us with a new outlook towards the development of wireless bio-sensor networks which do not need any particular medium in order to communicate with each other. This mechanism when perfected will be of immense help since it avoids the underlying “communication media” constraint faced when we consider Quorum Sensing as the interaction process.

IV c. Response capture and interpretation

Quorum Sensing explains the observation of luminescence in bacterial cultures. This phenomenon is exploited by measuring the luminosity of the resulting culture as and when it is released into the test environment. Several existing mathematical models can describe the growth of spoilage micro-organisms in chill environments. In fact, the growth rate of food borne bacteria is dependent upon environmental factors (e.g. storage temperature, acidity, water activity). Conversely, if we utilize the knowledge of growth rate, we may predict the environment; i.e., bacteria behavior may be used to read context in a minute scale in this case. The measure of luminosity by simple electronic devices gives us a measure of when the bacterial culture reaches the critical density with respect to the time elapsed since it was released in the test environment. Mathematical models mimicking bacterial growth rates can then be applied to provide data regarding various environmental factors. Measurement of Indole, Heal and Parsons (2002), gives us the resulting concentration of the bacterial culture that initiates the communication process. This data with respect to time elapsed since the bacterial culture was allowed to sample stimuli from the environment can be used to provide data regarding the various environmental conditions.

V. Bio-sensor PerNet

The sensor network thus derived from the usage of these bio-sensor nodes would be able to assimilate information on the basis of multiple stimuli input from the immediate environment in which the sensor network has been deployed. Deployment of live organisms is naturally automatic and self-maintained, Gassounon et al. (2001), that requires no effort from human side. A PerNet consists of A sensor network along with the requisite *middleware* to provide it with the respective features for developing the intelligent envelope for PerCom. ***Context-sensitiveness*** and ***context-awareness***, which are the hallmark of a successful pervasive system, are already in-built with respect to the live bio-sensors. This is substantiated by the very fact that bacteria determine their response to their environment depending on the very factors that define the environmental conditions. For example food spoilage by bacteria is dependent on the temperature of the environment in which it may infect the sample. Some of the rate laws are as follows: $Rate_g = K_{obs} (\mu_{max}C_s / (K_s + C_s)) C_c$ where $K_{obs} = (1- C_c/ C_P^*)$ and C_P^* denotes product concentration at which all metabolism ceases. The subsequent PerNet, referring to Fig. 5 and Fig. 1, formed on top of the Sensor network consisting of the Bio-nodes has middleware has embedded pervasiveness support built into it. Again we observe that the live bio-sensors prove superior in terms of their capabilities to offer in-built Pervasive support, thereby reducing dependency on associated middleware.

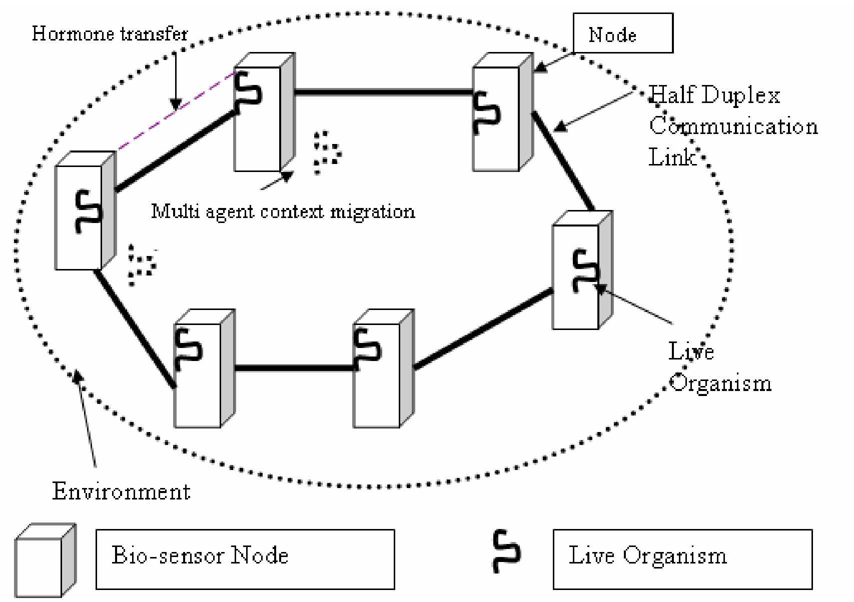

Figure 5. A basic view of bio-sensor network, with live organisms functioning as the agent entities, with provision for hormone transfer to aid in Bio-Agent context transfer to respective fusion point.

VI. Discussion

The idea presented here charts the future path towards the development of systems which use live bio-organisms as the very basic information gathering units. Pervasive computing which has not yet been able to unobtrusively integrate itself into the human domain can now achieve its goal by using the very basic live organisms to gather data on an immense scale and in as much detail as is afforded by the chosen organisms behavior to external stimuli in the test environment. This paves the way to designing bio PerNet and PerCom systems which will be able to harness the true potential of nature’s creations for the benefit of mankind. This work is seminal in the development of autonomic applications that are self-defining, self-configuring, self-healing, self-optimizing, self-anticipating and contextually aware of their environments. Further work in this direction will lead to design of protocols and behavioral studies specific to organisms deemed suitable as being amicable to the proposed architecture. This will allow for bio-nano-technology to play a major part in the development of PerCom to benefit subscribers of such new age services. However, thus far, most of the research activities in this arena have assumed the sensor nodes to be tiny electromechanical objects, which have their own limitations, Akyildiz et al. (2002).

VII. Conclusion

Our research has comprehensively provided a model to integrate live bio-sensor nodes into conventional sensor networks. A hierarchical functional classification regarding the abilities of a live bio-sensor alongwith the topological description of the sensor network subsequently formed from the usage of these nodes is provided. The associated rationale for selecting biological organisms to replace their electronic counterparts has been succinctly discussed at various places in the literature. Our proposal proves that a cost effective and more Pervasive inclined sensor network is formed from the use of these bio-sensor nodes vis-à-vis electronic sensors. It is an indispensable tool for the development of autonomic applications that are self-defining, self-configuring, self-healing, self-optimizing, self-anticipating and contextually aware of their environments The greatest potential comes from autonomous distribution of many small organisms around the environment to be monitored and thereby leveraging off close physical proximity between bio-sensor/actuator and the physical world. The novel target sensors and environments present unique challenges in the design of pervasive sensor networks, which are being actively analyzed in this project.

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