Invited paper

BIONETS: a New Vision of Opportunistic Networks

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[1]***Abstract*-Most wireless networks are built around an infrastructure, where all communications are routed through base stations that act as gateways between the wireless and wired network. However, there may be situations in which it is impossible or not economically viable to build such an infrastructure. In these cases, a collection of wireless mobile nodes could self-organize into a temporary ad hoc network, leveraging nodes mobility to provide system-wide information dissemination. The goal of the BIONETS project (BIOlogically-inspired autonomic NETworks and Services) is to provide a biologically-inspired open networking paradigm for the creation, dissemination, execution, and evolution of autonomic services, able to adapt to the surrounding environment and user needs, to evolve without direct human supervision, and able to deal with large-scale networks of heterogeneous nodes ranging from small, cheap devices to more complex network nodes. In this paper, we review the most innovative aspects of the research activities carried out by the BIONETS project consortium, focusing in particular on two novel information dissemination strategies.**

I. INTRODUCTION

The motivation for BIONETS comes from emerging trends towards pervasive computing and communication environments, where myriads of networked devices with very different features will enhance our five senses, our communication and tool manipulation capabilities. The complexity of such environments will not be far from that of biological organisms, ecosystems, and socio-economic communities. Traditional communication approaches are ineffective in this context, since they fail to address several new features: a huge number of nodes including low-cost sensing/identifying devices, a wide heterogeneity in node capabilities, high node mobility, the management complexity, and the possibility of exploiting spare node resources.

BIONETS aims at a novel approach able to address these challenges. Nature and society exhibit many instances of systems in which large populations are able to reach efficient equilibrium states and to develop effective collaboration and survival strategies, able to work in the absence of central control and to exploit local interactions. We seek inspiration from these systems to provide a fully integrated network and service environment that scales to large amounts of heterogeneous devices, and that is able to adapt and evolve in an autonomic way. Such an approach builds on previous work, which revealed the ability of nature to provide useful design guidelines for the design of distributed computing systems [1].

BIONETS overcomes device heterogeneity and achieves scalability via an autonomic and localized peer-to-peer communication paradigm. Services in BIONETS are autonomic, and evolve to adapt to the surrounding environment, like living organisms evolve by natural selection. Network operations will be driven by the services, providing an “ad hoc” support when and where needed to fulfil users’ requests. Security issues will be considered as a fundamental part of the services themselves, representing a key ingredient for achieving a purposeful autonomic system. This new people-centric paradigm breaks the barrier between service providers and users, and sets up the opportunity for “mushrooming" of spontaneous services, therefore paving the way to a service- and user-centric ICT revolution.

In this paper, we review the most innovative aspects of the research activities carried out by the BIONETS project consortium members. The focus is on networking, where opportunistic communications are leveraged to efficiently support evolving services. In particular, we present two novel mechanisms for achieving efficient dissemination of data in social groups of users.

The remainder of this paper is organized as follows. In Sec. II we review the fundamentals of the BIONETS project, highlighting the most innovative aspects on the networking side. In Sec. III we present, as project highlight, two innovative mechanisms, inspired by the functioning of biological systems, for achieving efficient data dissemination in a BIONETS environment. Sec. IV concludes the paper discussing on-going activities within the project consortium.

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II. OVERVIEW OF BIONETS

A. *Disappearing network paradigm*

We propose a communication architecture based on the "disappearing network" paradigm: networks exist only when and where needed. Two principles underpin this paradigm:

1. An embedded autonomic peer-to-peer model based on localized and occasional information exchange, and supporting a large range of device capabilities, ranging from billions of extremely cheap tiny devices (called T-Nodes, e.g. sensors, actuators, RFIDs) to more sophisticated mobile user devices (called U-Nodes, e.g. PDAs, notebooks, phones, etc.). In this context, the network as we know it in the traditional sense will disappear and will be replaced by occasional opportunistic information exchanges between T-Nodes and U-Nodes, among U-Nodes, and when necessary between U-Nodes and gateways (access points or AP-Nodes) to existing network infrastructures.

2. Service-triggered networking, in which "communities of interest" of users determine the services to be run, and these services determine the underlying communication information format and protocols necessary to support them. The communication paradigm, instead of preceding the definition of services, will be strictly embedded within them. The network moulds itself to the services in an autonomic way. This is in contrast with traditional systems in which the users must learn and comply with the requirements imposed by the technology.

We research biologically-inspired solutions to self-organization and self-management, with social networks of trust and reputation. This can be done by injecting user feedback and reputation information as fitness criteria for adaptation. This combination is used to build user- and environment-aware services that are also robust, secure, able to deploy, manage and protect themselves, and continue to evolve and maintain themselves after deployment, without requiring human supervision.

B. *Autonomic Self-Organizing Services*

The Autonomic Computing Initiative [2] places a great emphasis on self-management, self-healing properties, self-configuration and self-optimization. The same set of properties represents the basis for the definition of an autonomic communication system [3]. In the BIONETS project, we associate these properties with the general concept of self-organization, whose principles we derive mainly from biology. While many of the sophisticated (self-organizing) mechanisms that characterize biological systems evolved over long periods of time, they do not rely today on evolutionary processes in order to operate. Evolution could then, in principle, be regarded as the mean through which self-organization is achieved in complex systems. On the other hand, nobody but the environmental pressure guides evolution, so that, strictly speaking, it can be seen as a form of self-organization. Nonetheless, recent trends in theoretical biology suggest that the "survival of the fittest" paradigm (based on the mutation, cross-over, and selection operators) alone cannot be understood as the driving force of evolution toward more and more complex forms of life. BIONETS defines an autonomic framework, based on bio-inspired concepts, for providing stable operations and service management functionalities in a fully distributed and decentralized way. BIONETS will go for service evolution as the fundamental direction for enabling autonomic services. BIONETS will define and design an innovative framework for the creation, dissemination and evolution of autonomic services, able to survive and evolve in a dynamically changing and heterogeneous environment, without relying on a centralized control. Service implementations are regarded as "genes" from an organism that must live in a competitive environment and survive natural selection pressure. Such one-to-one mapping from services to biological entities will be carried out at different levels (in a fractal-like fashion), so that, at different levels of abstraction, genes could be, e.g., some service parameters that need to be dynamically adapted, some blocks of code to be composed, some instruction to be used to build a meaningful and efficient software code etc. The net result of BIONETS will be the provisioning of a digital ecosystem for autonomic services, able to users demands and needs in a transparent and efficient way by exploiting the unique features of pervasive communication/computing environments.

C. *Architecture of U-nodes and T-nodes*

There are 3 main actors in BIONETS networks, in terms of devices: T-Nodes, U-Nodes and APs [4].

1, *T-Nodes* are simple, inexpensive devices with sensing/identifying capabilities. T-Nodes act as interface with the environment and are needed to provide context-awareness to BIONETS services. T-Nodes do not communicate among themselves but are just 'read' by U-Nodes passing by. They present minimal requirements in terms of processing/storage/communications.

2, *U-Nodes* are complex, powerful devices. No stringent limitations on requirements are encompassed for U-Nodes. PDAs, laptops and smart phones represent examples of a U-Node. U-Nodes are carried around by users (hence they are 'mobile') and run services. They interact with the environment through T-Nodes, from which they gather information to run context-aware services. U-Nodes may communicate among themselves to exchange information, whether environmental data or service-specific code (in order to enable service evolution).

3, *Access Points* are complex powerful devices that may be used for (i) accessing IP-based services by the BIONETS networks (ii) collecting environmental data (through BIONETS system) from a remote IP service (iii) providing IP shortcuts among disconnected BIONETS islands. APs are envisioned to act as proxies between BIONETS networks and IP networks.

D. *Communications in BIONETS*

The BIONETS system has a layered architecture, where the lower layer is composed of devices interfacing directly with the environment. Such devices as introduced above, the T-nodes, are in charge of providing information on the surrounding conditions to the devices carried by users; the latter devices, the U-nodes, form the upper layer of the system architecture, and are in charge of hosting a large variety of services. In the BIONETS project, we use often the term network but it is understood that this term is misleading with regard to the system at hand. In fact, there are two reasons why the strict customary term network does not fit. The first reason is related to connectivity. The lower layer is indeed completely disconnected. The economic and technical reasons for this architectural choice are described in [5], and will not discussed further in this paper. On the other hand, a major outcome of [5] is that scalability reasons suggest that, even at the U-node layer, we should not rely on connectivity at each point in time. If we put these two features together, the term network is indeed inappropriate for the BIONETS communication architecture: to a certain extent, the BIONETS network paradigm is truly dissolved over time at the U-node layer, and reduced to mere point-to-point or local broadcast at the T-nodes layer. Nevertheless, the communication architecture of BIONETS works on a concept of connectivity over time. The mechanism to gather sensed data and to diffuse them into the environment, in fact, relies on the U-nodes movement and on a peer-to-peer data exchange. To this extent, contacts among U-nodes represent the true engine of the opportunistic diffusion process and propagation of messages is constrained to the actual user mobility pattern. The BIONETS communication system is able to interface with the networks with a central infrastructure, using access points.

E. *Security issues*

Given the adaptive nature, security is a major issue in BIONETS. Apart from the deployment of security mechanisms which perform adaptation depending on the environment and communication partners, practical and new combinations of adaptive security mechanisms are delivered. For instance, combined with newly developed secure routing techniques, trust and reputation mechanisms have to be used to yield innovative approaches which will try to increase network resilience, adapting to existing threats or attacks within the network. Due to the heterogeneity of BIONETS the project will also deliver new techniques to provide privacy, anonymity and authenticity. The project will go one step further and coin a new security paradigm: “evolutionary security”. Rather than adapting security in a pre-defined way (e.g. by negotiation), evolutionary security aims at changes in security architectures or services that are controlled by feedback/guidance from the environment. A thorough investigation of this new approach and its appraisal are additional goals of this project.

Note that the new paradigm should not replace but rather complement the current networking infrastructure: AP-Nodes will always remain in the landscape and will likely help the aggregation of U-Nodes, with possible room for the definition of coalition and competition in the clustering of U-Nodes. The new bio-networks will be interconnected to and will enhance the services offered by conventional telecommunications systems such as wireless access systems (cellular networks, hot spots) and the Internet.

III. HIGHLIGHTS OF BIONETS

As we stated earlier, the communication architecture of BIONETS is based on a concept of connectivity over time. The

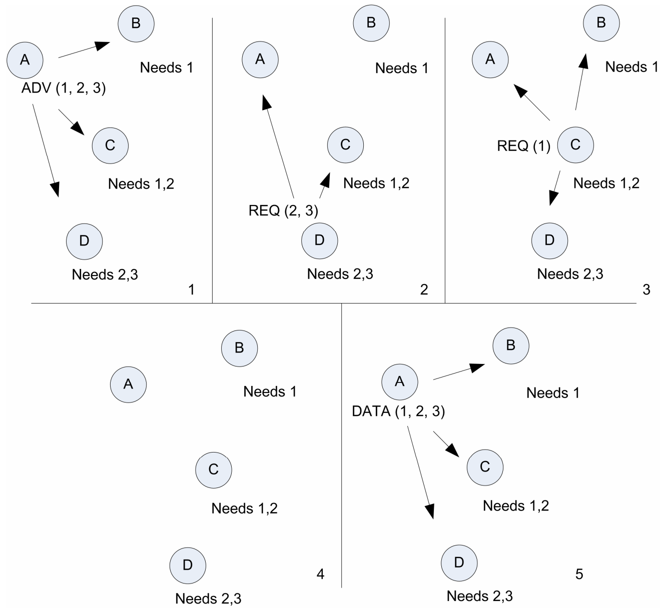

Fig. 1. General model of IOBIO

data dissemination in the system relies on the movement of U-nodes and on a peer-to-peer model for data exchange. In this case, contacts among U-nodes represent the true engine of the diffusion process and propagation of messages dependent on the mobility of the U-Nodes. In general, we expect BIONETS type of systems to be characterized by a rather low density of U-Nodes. Nonetheless, there may be situations in which flash crowds of users (and of U-Nodes) arise. In such situations, it is of foremost importance to have dissemination techniques able to scale well with the number of devices. Therefore our main concern is to find an efficient way for information dissemination between the U-nodes, to reduce the total amount of the sent data together with the delay experienced by the nodes.

A. *The IOBIO protocol*

In BIONETS the communication between nodes can occur in two ways: between two U-nodes, or between a T-node and a U-node. It is important to note that there is no addressing (at least in the traditional end-to-end sense) in BIONETS networks. For battery saving and other reasons simple periodic broadcasting is not an efficient way of communication. We also have to consider that users are usually not interested in every type of data. They form User Communities (UC) with similar interests. [6]

1., Overview of the Protocol: In our IOBIO protocol the nodes use three different types of messages for information-exchange.

ADV: advertisement of new data. If a U-node intends to send out new information it first sends an ADV packet that describes the data packet. The advertisement contains the identification information for the targeted UC. ADV messages are sent periodically.

REQ: request for data. A U-node answers to the ADV packet with REQ, asking for the advertised information.

DATA: the data message, which contains the requested information.

Although this protocol seems to be simple, different issues should be considered (e.g. Are U-nodes allowed to send collected, summarized or anyhow aggregated data or not?)

2. General steps of the protocol

a. A U-node (A) (who is a member of a certain UC) receives a data packet from a T-node or from another U-node.

b A broadcasts an ADV message.

c. A U-node (named B) is a member of the same UC as A. B checks the ID of the advertised service, and it concludes that it needs that information. B broadcast a REQ message.

d. A receives a REQ message. A checks the ID of the requested information. If A does not have this information, A drops the message, otherwise A sends out the DATA packet referred to by the REQ message.

e. A broadcasts the requested DATA, B receives it. B processes it and then starts the IOBIO protocol from point b) (e.g. broadcasts an ADV message).

3. Resolving advertisement collisions:

In order to resolve the problem of *advertisement collision* the following scenario is presented. We assume that two nodes – A and B – send an ADV message at the same time. If there is a U-node (named C) in the communication area which is interested in this information, both A and B will receive the REQ message. It may lead to overhead if both of them send the DATA. In order to avoid this we extend our protocol the following way. If a U-node (named A) sends an ADV message, and it receives the same ADV message (from another U-node, named B), it draws a random number, and sets up its waiting-time to this random number. Node B does the same. If A receives a REQ message, it will wait for the set delay – if it does not receive a DATA information with the requested data during the waiting-period, it sends the requested information. If it receives the requested data – which means that the information was already sent by B – it does not send anything.

If we investigate *information carrying* we can observe the following: at first we assumed that the information flows only between U-nodes that belong to the same UC. But it is possible that the members of this group are separated. We let the U-nodes carry information which belongs to other UC with some probability.

4. Advantages of the protocol

One of the most useful properties is the limited overhead - no unnecessary DATA message is sent. With the 3-stage handshake we do not need to broadcast every time. The first and second steps use short control messages; the broadcasting of the data only happens in the third step, and only when it is really needed. It happens only upon a request nearby –thus, the overhead is decreased.

We assume that a lot of U-nodes – belonging to the same group of interest – are usually close to each other. In this case lot of advertisement and request messages are sent, and the networks will work as a simple broadcast-network. One can tell that with the 3-stage handshake the energy needed for communication, because the U-node sends only short advertisement messages (which message should be processed by all the nodes in the communication range), and all the data will be sent only in one case: if a node needs it.

B. The Modified IOBIO (MIOBIO) protocol

The IOBIO uses simple periodic broadcast to send ADV packets. Earlier investigation showed that considering the number of packets a more effective approach is possible. We developed The Adaptive Periodic Flood (APF), which is a simple controlled flood protocol that can reduce the number of duplicated messages without using control messages, while maintains low delays and robustness that are characteristics of a Blind Flood [7], [8].

The APF is based on two event handlers and can be described as follows:

```
if Timer expires
  broadcast a message
  increase Timer to now + period
end if;
if a message is arriving
  if messsage is new then
     increase Timer to now + period
     set message to broadcasting-message
  end if
  else
     increase period with delta
end if
```

This simple protocol broadcasts messages periodically, and increases this period when a duplicate arrives.

Considering the number of bits sent/received APF is not as efficient as IOBIO because it sends DATA messages only, and generates a high amount of unnecessary bits. IOBIO is able to avoid the transmission of unnecessary DATA messages using a simple handshake. To combine the benefits of the two algorithms, MIOBIO uses the APF protocol to decrease the amount of duplicate ADV messages, and uses the original IOBIO handshake to decide when DATA messages have to be sent. The IOBIO and MIOBIO – similar to other networking strategies [9] - leverage opportunistically contacts among nodes to spread information system-wide. In the opportunistic networks no assumption is made on the existence of a complete path between two nodes wishing to communicate. Source and destination nodes might never be connected to the same network, at the same time [10].

C. Multi-Message Scalable Broadcast Algorithm (MMSBA)

The algorithms that do not take partitioning into account, like Scalable Broadcast Algorithm [SBA] and Generic, perform poorly in disconnected environments. These kind of algorithms decide to rebroadcast a message only once, when it is first received. If there are no more nodes in transmission range when the last message is sent, the dissemination stops. Unfortunately, when a new node arrives into the transmission range, there is no event that can trigger a retransmission. To solve this problem, we improved the SBA algorithm, because it is computationally simple, and proved to be robust by many papers [11], [12]. It also gives a nice way to generalize its mechanism to the multi-message case. The basic idea of the SBA algorithm is the Random Assessment Delay [RAD] process, which delays the transmission of packets by a random interval. The first time SBA receives a packet, it starts the RAD procedure. During this interval the SBA listens to his neighbours. When one of them starts broadcasting, SBA removes the neighbours of the broadcasting nodes from his own 1-hop neighbour set. Our modified algorithm, the Multi-Message SBA (MMSBA) may trigger a RAD not only on the first reception of a message, but on any event that changes the local neighbourhood information. Every time a HELLO message is received, MMSBA updates his neighbour list. When the number of interested nodes exceeds zero, MMSBA starts the RAD. The RAD works exactly the same way as in SBA. There is a little problem though. Every time we receive a HELLO message from another node, we will put him again on the list of interested nodes, even if the broadcast message was already sent to him. This problem is not present in the original SBA, as nodes broadcast the message at least once, when it is first received. To overcome this problem, the nodes include the list of messages they have already received in their HELLO packets. This also gives a feedback to MMSBA if a broadcast message was lost during transmission. The new method allows MMSBA to handle many messages independently.

D. Mobility Models for the BIONETS environment

The validation of various protocols is highly dependent on how realistic the used mobility model is. Since mobility patterns play a significant role in determining the protocol performance, it is desirable for the mobility model to emulate the movement pattern of real life scenarios in a reasonable way. The problem is that there is a very limited number of available real mobility patterns [13], [14] capturing node movement in large-scale disconnected mobile networks. Not only the amount of mobility patterns is limited, but these traces are related to very specific scenarios and it is difficult to generalize.

However none of these synthetic mobility models reflect real world situations, because in practice, a mobile node does not roam in a completely random manner. In the BIONETS mobility environment the delicate details of time-location dependency and community behavior must be taken into consideration. In these networks it is important to model the behavior of individuals moving in groups and between groups, therefore the mobility model in this case must be heavily dependent on the structure of the relationship among the mobile nodes, capturing this social dimension. A key aspect of human movement is dynamic clustering. We can observe this on the streets: people travel in small groups (clusters); some people join the clusters, while others leave them [15]. Clusters form in traffic jams, on mass transit vehicles, etc. To examine this phenomenon we have developed a group mobility model, called the Reference Point Group Mobility Model with Dynamic Clustering (RPGMMDC) [7]. It is a modified version of the Reference Point Group Mobility Model (RPGM) [7], which is a group mobility model and it means that the nodes are organized in groups and the groups move together. Each group has a center point, that moves according to a mobility model (in our case the Constant Speed Mobility Model). Each node has a reference point close to the center point, and sets its destination in a random location near the reference point. In the RPGM model, the groups were predetermined, and did not change during the simulation. In our modified version, after each step each node has a small chance of leaving the current group and joining another randomly chosen group. This model offers an even more accurate representation of human movement: groups mentioned in the previous paragraph change over time; some people join the group while others leave and eventually join another one.

E. The BIONETS Simulation Framework

Within the framework of the BIONETS project, a freely available simulation tool has been developed [16], extending the architecture and functionalities offered by the well-known OMNeT++ [17], [18] package to reflect the BIONETS system architecture. The main goal of the simulator is to provide a tool

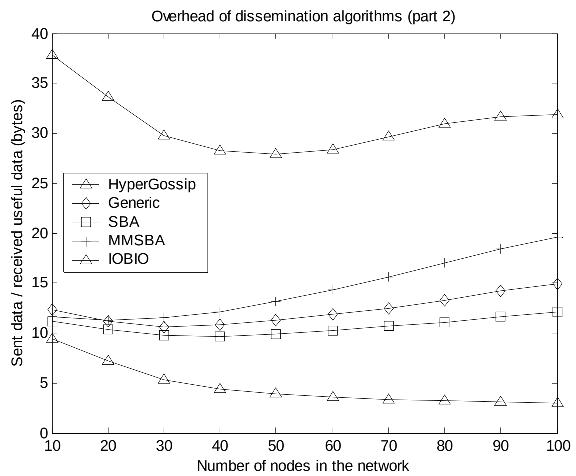

Fig.2. Reliability of the simulated algorithms using Constant Speed Mobility

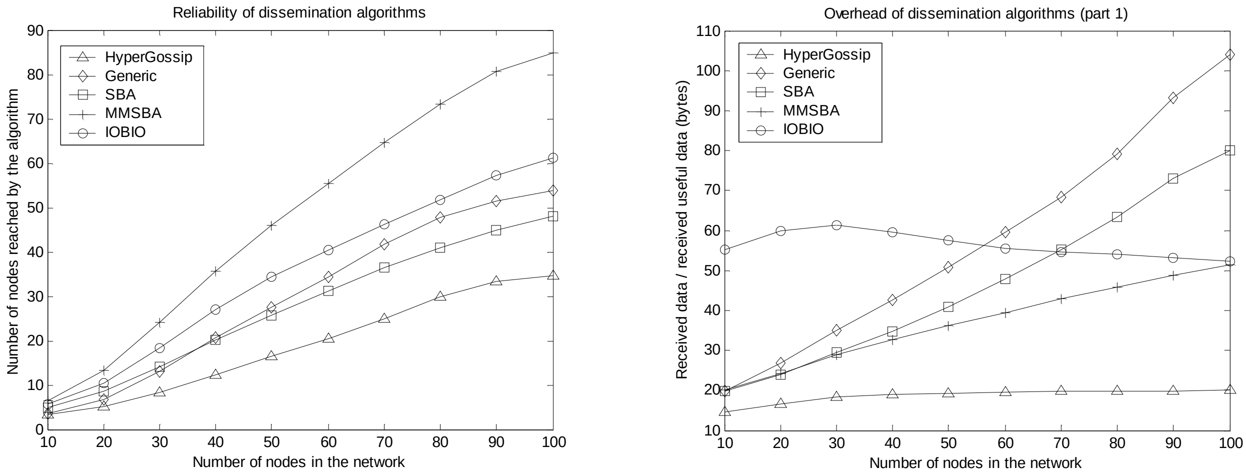

Fig. 3. Constant Speed Mobility; data received/useful data (on the left), data send/useful data (on the right)

for all the participants of the BIONETS, which help they can implement and simulate their early ideas and novel algorithms Another goal is to help experimentation with novel ideas that will be incorporated in BIONETS. Such the simulator is designed to support quick prototyping and fast realization of ideas. There is also a great emphasis on flexibility. The simulation framework itself is a collection of interdependent software components. The heart of the system is the OMNeT++ discrete event simulator library and tools. The Mobility Framework [19], [20] is a library built on the OMNeT++ core library which provides a framework for mobile communication simulations. It contains several implemented modules. Simulator components provide additional or customized services on top of OMNeT++ itself have several components. The core library is the implementation of the discrete event simulator which executes a simulation model that can be defined by the simulator users. Mobility framework is a library that provides a framework for mobile ad hoc simulations and also has different model implementations. It supports the use of different mobility and channel models, and many network technologies.

F. Results

We have used the simulator to evaluate the performance of different information dissemination algorithms and mobility models, presenting the two novel information dissemination algorithms, the Multi-Message SBA (MMSBA) and the Modified IOBIO (MIOBIO), comparing them with the reference algorithms chosen from the literature [11], [12], which are the best available dissemination methods published earlier for a BIONETS environment: Generic Self-Pruning [21], SBA [22], Hypergossiping [23]). These algorithms were chosen after an extensive study of the literature of data dissemination, covering a large set of different dissemination types, drawing a conclusion that the three algorithms mentioned above give a very good all-around solution that performs well in the BIONETS environment. The main criteria for the evaluation of the algorithms was the robustness of the algorithms in different conditions. The simulation parameters were chosen to be realistic to be able to test the algorithms in a BIONETS like environment. Every simulation starts with a 200 second "warm-up" period (needed by the mobility models). The transmission of the control messages (like HELLO) starts after the 195th second, so the dissemination methods have time to discover their neighbors. The first message is broadcasted from a single node at the 200th second. It is assumed that the message has 10 seconds lifetime, so the simulation stops at 210 seconds, when the message gets outdated. Every point in the graphs was averaged over 100 runs. For all the algorithms under investiagation, we measured the number of the nodes that correctly received the message within a delay of 10 sec. The results of these measurements are shown on Figure 2. The results show that MMSBA provides the best coverage for the Constant Speed Mobility, but using other mobility models, the performance of IOBIO and MMSBA is very close. Both of the new algorithms outperform SBA, Generic and HyperGossip. We are interested in the rate of received and useful data, and also in the rate of send and useful, because these must be processed by the Information Filtering module in U-Nodes, and this can be a serious computational overhead. The results of the simulations can be seen on Figure 3. In this case IOBIO is the clear winner.

IV. CONCLUSION

In this paper, we have presented some of the innovative research activities undergoing within the framework of the BIONETS project. In particular, we focused on the innovative aspects concerning the relaying, filtering and dissemination of data messages within the network, which build the basis of the so-called "Disappearing Network" paradigm. Two new techniques for achieving efficient data dissemination in BIONETS-like networks were presented in details, together with the outcome of a simulative study carried out to analyze their performance. Activities within the consortium are now focusing – among the other topics - on methodologies and tools for embedding evolutionary features into such kind of data dissemination schemes.

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