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Bio-Inspired Monitoring of Pervasive Environments

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***Abstract*—Successful deployment of the pervasive computing paradigm is based on the exploitation of the multitude of participating devices and associated data. It becomes therefore evident that there is a necessity to provide optimal resource discovery mechanisms, the effectiveness of which will constitute the foundation for the efficient operation of pervasive computing environments. To mitigate the drawbacks brought by the inherent nature of pervasive environments, i.e. dynamicity, heterogeneity and scalability of the network infrastructure, we propose to employ P2P overlay networks that lead to more manageable topologies and optimize resource monitoring by scaling down the degree of complexity. In particular, we take advantage of bio-inspired self-organization mechanisms to construct reliable P2P overlays and thus provide more robust and adaptive monitoring solutions. High-level policy-based management operations driven by monitored context information enable a further level of runtime adaptation and optimization, subject to the overall application requirements. We report here on our ongoing work in this research area.**

I. Introduction

The proliferation of ubiquitous networking solutions experienced in the last few years in the context of ever popular pervasive application scenarios and the high rates of user adoption of wireless technologies lead us to believe that there is an established paradigm shift from traditional, infrastructure-based networking towards wireless, mobile, operator-free, infrastructure-less networking [1]. The latter constitutes the foundation of existing and prospective pervasive environments. To effectively manage such environments, P2P overlay networks are increasingly built on top of heterogeneous wired and wireless networks to mitigate their drawbacks regarding scalability and topology instability and to allow for efficient resource discovery by means of monitoring (e.g. [2], [3]).

When designing reliable P2P overlay networks, the emerging requirements from the underlying networking infrastructures have to be taken into consideration, e.g. mobility, dynamic topologies, node failure. Moreover, the inherent nature of pervasive environments necessitates the distributed construction and maintenance of such overlays, since centralized solutions over dynamic network structures are not scalable and suffer from the presence of a single point of failure. In our view, robust P2P overlays can be designed by taking advantage of the beneficial properties of bio-inspired mechanisms, such as those exhibited by swarms and ants. These mechanisms rely on self-organization and make use of localized information to optimize, in terms of specific criteria, the entire network, while additionally supporting robustness and adaptation in highly dynamic situations.

Building on our previous work that was applied in grid systems [4], we present here our initial work on addressing the provision of reliable monitoring of pervasive environments, by exploiting bio-inspired P2P overlay networks. The core of our work is a P2P overlay algorithm based on the behavior of ant colonies, which adaptively optimizes the overlay structure in terms of different cost functions (e.g. maximum link delay to support QoS guarantees). To achieve a further degree of adaptation, we also consider a higher-level policy-based management layer capable of reconfiguring the aforementioned monitoring scheme. This layer operates in the background, collecting context information, processing them, matching them to policy conditions and inferring necessary configuration changes that are enforced in order for the monitoring layer to adjust its functional behavior, e.g. by reconfiguring the underlying protocols to reflect varying requirements.

In this paper we present a unified architecture encompassing both the aforementioned monitoring and management layers. Their integration effectively leads to an autonomic management cycle, where the ant-based monitoring mechanisms are continuously optimized by the management layer using a context-aware, policy-based approach. Our work also serves as a proof-of-concept of the merits of the synergy between bio-inspired and pervasive computing.

The rest of this paper is organized as follows. Section II presents an overview of related work on adaptive P2P overlays, while Section III introduces the proposed architecture and describes its monitoring and management layers. Section IV details preliminary evaluation results regarding the ant-based P2P overlay. Finally, Section V concludes the paper and provides insights to future research directions.

II. Related Work

Bio-inspired methods and techniques have found applicability in complex systems management, especially in cases where reliability and flexibility are required, since they have desirable properties such as robustness to failure of components, ability to be adaptive to changing conditions and lack of necessity for centralized control [5]. In particular, emergent behavior coupled with self-organizing capabilities both provide the increased reliability and scalability that is desired in distributed systems along with the ability to react and adapt to unexpected situations. Such methods are more and more necessary to face the dynamics of current heterogeneous networks and their management by means of P2P overlay networks, i.e. logical structures requiring constant adaptation in the way that they are coupled to physical networks [6].

Considering the field of network management, a general framework based on swarm intelligence principles was presented in [7] to handle related issues. Moreover, bio-inspired management of topologies in unstructured P2P overlay networks was discussed in [8], by proposing epidemic and gossip-based protocols for load balancing and search. The T-Man protocol introduced topology management for structured overlay networks using the model of cell adhesion that has been studied in developmental biology [9]. Several P2P and grid systems use ant algorithms for scheduling, load management and resource discovery purposes such as Messor [10] and Anthill [11], while the recently proposed Self-Chord framework [12] allows for the efficient construction and maintenance of a load balanced P2P overlay using self-organized ant-like agents.

Whereas the aforementioned approaches bear significant benefits in terms of efficacy and adaptivity, their configuration settings remain unaware of the actual network conditions and are also bound to the initial optimization criteria. Taking into account the dynamicity of pervasive computing environments and the possible change in application requirements, we propose an additional level of adaptation based on collected context information and high-level management policies. Similar approaches include the MobiPADS middleware [13] that uses context information to enable application adaptation, as well as a context-driven autonomic approach to MANET management based on high-level policies that was studied in our previous research [14]. The middleware approach for the reconfiguration of mobile applications presented in [15] is conceptually close to the work we plan to undertake, albeit applied on services state migration, while in the direction of using intelligent agents, as in our case with ant-like agents, a middleware for the context-aware adaptation of ubiquitous services is presented in [16].

III. Architecture

Figure 1 depicts a heterogeneous network scenario, where a P2P overlay network is employed to increase scalability and reduce complexity. Resource discovery mechanisms operate on the overlay to enable higher-level services and applications to query for information and the status of network resources in the overall pervasive environment. Flexible P2P overlay network adaptation is required to accomodate the variety of both application and network requirements. Extensibility is also of primary concern, in order to fulfill potential configuration changes that have not been conceived at the time of design or simply because the initial optimization criteria have been revised. We have consequently selected to exploit Policy Based Management (PBM) principles to benefit from their support for both flexibility and extensibility [17]. Policies, defined as event-condition-action rules, are utilized to indicate the necessary overlay configuration changes upon the occurence of specific context-driven events in the pervasive environment (monitored by means of the bio-inspired P2P overlay). In this respect, context information needs to be disseminated across the network, leading to the requirement for efficient management of the context distribution so as not to overload the underlying network and to effectively ensure the timely operation of the architecture. In order to reach these objectives, we opt for a modular architecture (Figure 2) comprising two layers to allow for flexibility and extensibility, while additionally supporting a clear separation of concerns.

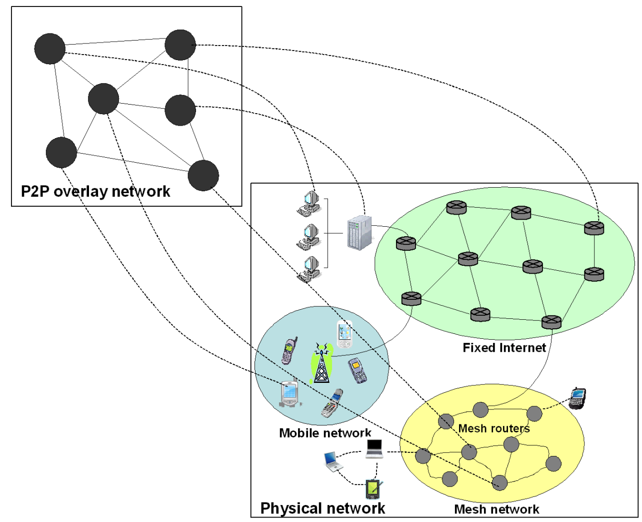

Fig. 1. Monitoring pervasive networks with the use of P2P overlay networks

Network monitoring layer: It is inspired by swarm intelligence principles and in particular ant-based algorithms for the construction of a P2P overlay on top of pervasive networks in order to increase resilience against dynamic changes. It is responsible for the monitoring of network devices and their status, as well as of data and services related to the pervasive environment itself. A set of interfaces is exposed to higher layers in order to query for and retrieve information.

Network management layer: It is in charge of deducing configuration changes to be employed on the monitoring layer based on context information collected from the pervasive environment and policy-based management principles. Pervasive applications that require access to information register their interest with the information discovery component.

A. Monitoring Layer

Monitoring is performed over a bio-inspired P2P overlay network, by exploiting limited and selective flooding techniques similarly to our previous work [4]. The algorithm to create and maintain the P2P overlay network is based on a number of ant-like agents that operate on the network by migrating across nodes and optimizing the virtual overlay topology according to specific cost criteria, e.g. maximum link delay or characteristics of physical network connections. It is important to note that the ant-like agents perform changes in the topology locally for every node that they visit, but the distributed nature of the proposed ant-inspired algorithm (based on the principles of Ant Colony Optimization [18]) ensures that optimization occurs for the entire overlay topology.

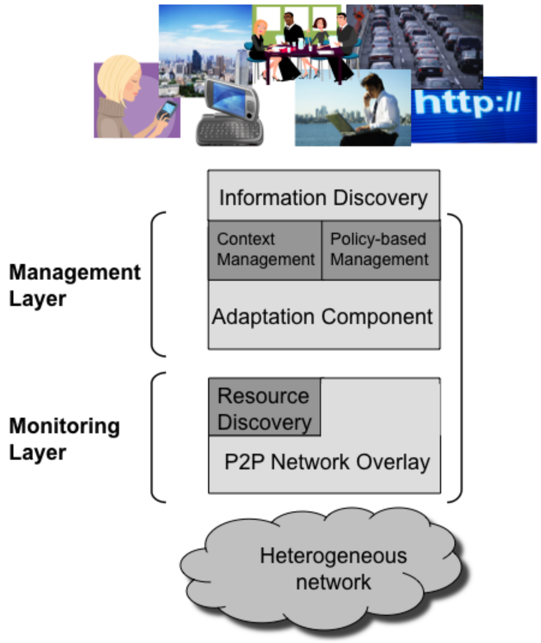

Fig. 2. Modular architecture to monitor pervasive environments

The proposed overlay management algorithm is fully distributed; nodes do not have global information on the network topology. Ant-like agents roaming the network collect and disseminate information about the neighbors of nodes and thus eventually assist in nodes formulating a wider picture of the overall network topology. Additionally, further information about the network nodes is being distributed in order for the nodes to be able to calculate the cost of links as previously explained. Starting from a logical overlay topology matching that of the physical network, overlay links in every node are re-arranged according to two simple rules. The first involves creation of new links to optimize the topology; a new link is created between two non-connected nodes if the cummulative cost of the path between them is larger than a user-defined optimization parameter *max_cost*. For example, QoS guarantees might be offered when maximum delay is used as the cost criterion, leading to bounded delay overlays and hence delay-constrained resource discovery. The second rule aims at removing cycles from the overlay that reduce the performance of monitoring mechanisms, due to the high probability of visiting the same nodes and in particular in wireless environments because of the inherent nature of the transport medium, i.e. hidden terminal problem. The second rule removes overlay links that are part of cycles of length less than a user-defined parameter *min_cycle*. To avoid network partitioning only one node in a cycle is allowed to break it, in which case it unidirectionally informs the remaining cycle nodes of this action to prevent multiple breaks. In all cases, special attention is given to retaining the node degree bounded and balanced across all nodes to avoid the creation of hubs.

These two local rules lead to the creation of an optimal, according to specific cost criteria, P2P overlay network. It should be noted that the migration of ant-like agents is based on the real-world notion of pheromones, i.e. agents preferably follow frequently visited paths since they are most likely to be reliable. A significant feature of our algorithm is that is allows for the concurrent management of more than one P2P overlays, each adhering to a different cost criterion. Such an approach is tightly bound to our viewpoint of dynamically adapting the P2P overlay according to high-level requirements and allows the on-the-fly switch between different P2P overlay structures, in addition to local reconfigurations. An in depth description of our algorithm is omitted here due to space constraints.

B. Management Layer

Monitoring solutions are influenced by the adverse characteristics of pervasive computing environments and their underlying networks and even adaptive and self-organized approaches such as the bio-inspired ones will eventually require reconfiguration. The reason for this lies in the fact that the preset configuration settings of the bio-inspired monitoring algorithm are based on both specific network conditions (e.g. highly volatile or static topologies) as well as on particular optimization criteria (e.g. optimize in terms of delay or path length), which are both subject to changes. Consequently, there is a need for techniques that mitigate these problems in order to enable efficient network management and monitoring. We therefore introduce a management layer that resides on top of the monitoring layer and guides the adaptive reconfiguration of the monitoring algorithm based on available context and predefined policy rules.

The management layer is composed of three components, i.e. context management, policy-based managemenent and adaptation. Context awareness, achieved by means of the context management component of our architecture, assists in building more predictable and thus more reliable long-term pervasive environments by providing higher and lower level information regarding the participating nodes, which can aid in predicting their current and prospective status. When such knowledge for each and every node has been predicted and disseminated across the network by the context management component, the future topology and conditions of the network can be foreseen, allowing thus for the proactive and failsafe adaptation of the P2P network monitoring protocol. In this respect, high-level management rules expressed as policies guide the reconfiguration of the monitoring layer. Since the reconfiguration of the P2P overlay algorithm is performed in a distributed fashion, both coordination and homogeneity of the configuration changes across all nodes need to be considered. The policy-based management component is responsible for the latter, keeping track of the active policies and ensuring their network-wide uniformity, while additionally interacting with the context management component to gain common understanding of the network context. The combination of shared context and common policies ensures effective and uniform distributed policy enforcement. Finally, the adaptation component is in charge of translating the high-level actions defined in the policies to specific configuration changes in the

P2P overlay. Space limitations prevent us from describing the proposed architecture in further detail.

IV. Evaluation

Preliminary experimentation regarding the ant-based overlay is based on simulation using the OMNET++ discrete event simulator, which we plan to extend by allowing it to interface with the management layer of our architecture that is currently under development. An aspect that we are interested in evaluating is the effect of the decentralized operation of the algorithm, in particular its efficiency to converge to stable overlays despite nodes having only a local view of the network, as derived by information collected by the ants. Figure 3 illustrates the effect of a growing per node local network view on the number of overlay edges. The results refer to an overlay optimized in terms of short average path lengths (hence the increasing number of edges) for a random network topology of 1281 nodes, which becomes dynamic (1 node joining and one living every 4 seconds) after 7200 seconds as indicated in the graph.

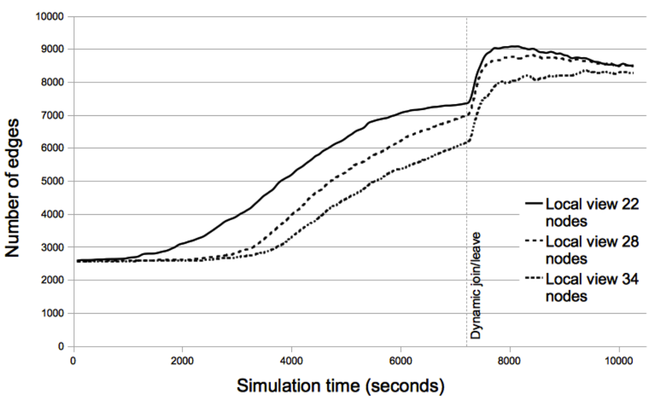

Fig. 3. Overlay edges for expanding local network view

It is important to note that in all cases the number of edges in the overlay converges to a stable state over time and even during the dynamic case convergence occurs quickly albeit the increase in the number of edges. The latter is attributed to the inherent adaptivity of the adopted bio-inspired approach. When only few information is available, nodes generate more edges to optimize the cost function, but they are usually redundant or could have been avoided subject to a wider knowledge of the network that would allow for a broader range of possible nodes to link to in an optimal manner.

V. Conclusions

We presented here our ongoing work on an integrated aproach to handle monitoring of pervasive environments, which incorporates bio-inspired techniques to optimize resource discovery as well as adaptive, policy-based management to guide the reconfiguration of the aforementioned techniques in accordance with higher level objectives. Moreover, having briefly described our proposed architecture, we illustrated encouraging preliminary results regarding efficient operation of our ant-inspired monitoring P2P overlay.

Our future work will focus on further experiments regarding P2P overlay optimization using our ant-inspired algorithm and the overhead of the latter. We expect that several overlay structures will be maintained and it will be the responsibility of the management layer of our architecture to decide upon the one that will be activated to perform monitoring and resource discovery based on the application requirements.

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