Nomadic Wireless Sensor Networks for Autonomic Pervasive Environments

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Abstract. Pervasive computing is one of the most promising research directions for the next future. More and more interest is devoted to the definition of protocols and paradigms for such challenging scenarios. It is envisioned that almost every object surrounding us will be accessible via some electronic device and will become, to some extent, a node of the communication super-structure. This, of course, will entail completely new problems to be addressed, since it will not be possible to manage a network composed by billions of nodes with traditional Internet protocols.

In order to overcome the aforementioned problems, we propose a novel communication paradigm that, despite its simplicity, provides a viable solution to the new all embracing pervasive environments, exploiting the implicit heterogeneity of the network nodes and the time/space dependence of the information circulating in the network. This article presents the approach and evaluates it through simulations in a real application scenario: a parking lot finding system.

1 Introduction

The term Pervasive Computing generally refers to an explosion of interconnected "smart devices" from watches to cars that can make our lives easier and more productive. According to this, in the future pervasive environments, we can expect the number of nodes to grow by multiple orders of magnitude as tags, sensors, PDAs, watches etc., get fully integrated into the communication superstructure [1, 2]. This will dramatically increase the amount of information to be managed, while reducing, at the same time, the processing and communication capabilities of the devices participating in the network.

The vast majority of the devices will be constituted by tiny small nodes that will be required both to sense and to communicate with other nodes in the near proximity. The limited capabilities and dimensions of these nodes, together with the limited energy available, pose severe constraints on their complexity and on the protocols they will be able to run.

As opposed to these small tiny nodes, there will be powerful users devices (e.g., PDAs, smart phones, laptops etc.), capable of intensive processing operations, of

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storing high volumes of data, and of performing high data rate communications. Today's cell phones will evolve into personal devices, which will be used not only for communicating, but also for supporting people in their daily life operations. Through the exploitation of the tiny devices information, users will be able to interact with a living environment, and their communication devices will represent the key driver for accessing such a digital ecosystem, and for starting to interact with it .

Hence, we envision a scenario where there will be a clear distinction in the role of the network nodes, and the network will be organized according to a hierarchical architecture. Nodes complexity and communication capabilities will scale with their role. The tiny nodes will act primarily as source of information, while the user devices as consumers of the generated information.

Moreover, the information circulating in the next generation networks is drastically changing in its significance, since it will be constantly localized in space and time, which means that, most of the time, information will be outdated and therefore useless with respect to the context where the user is moving in. It will be always possible to define a *local sphere* (both in time and space) within which the data represents useful information to the user.

Nomadic Wireless Sensor Network (NWSN) is a novel paradigm, firstly proposed in [3], for dealing with the described new pervasive environments. It exploits the implicit hierarchical structure of Next Generation Networks (NGNs) together with the physical mobility of users, in order to achieve an effective diffusion of the information in a totally distributed fashion. Sensor nodes will have the only role of broadcasting their information to mobile users in proximity, while all the complexity needed for transporting the gathered information, and for diffusing it, is shifted at the user nodes. Information is exchanged among users exclusively through single-hop broadcast communications. The applicability of such a network model is confined to a class of services requiring massive amount of data retrieved locally and with relaxed delay constraints.

The use of a hierarchical architecture and of mobility to improve network performance has already received some attention. In [4] a multi-tier network architectures is utilized to mitigate the scalability problems of creating a self-organizing network composed by thousands of heterogeneous nodes. In [5, 6] a multi-tier architecture is introduced for collecting data in a sparse sensor network. By exploiting the mobility of some nodes of the network, sensor data is gathered from the environment and transferred to the final users.

In Delay Tolerant Networks (DTNs) [7] problems related to intermittent connectivity, variable delay and asymmetric links are faced by adopting a store-and-forward policy. Most of the work is related to the analysis of packet delays, buffer dimensioning and routing strategies of the storing nodes.

All the referred work focuses on ensuring the delivery of packets from a source to a destination, either in the case of a disconnected network, or in the case of a network where the high number of nodes is too prohibitive to be managed. On the contrary, NWSN aims at a the pure diffusion of the information, which has been generated from sensors, in the environment where the users are moving in.

The major contribution of this paper is the definition of the NWSN architecture and related protocols, and the analysis of a parking lot finding system running on top of the NWSN. The performances of the NWSN network are evaluated through simulations and compared with the case of a centralized system. It is shown how, with an adequate mobility and number of users, the NWSN performance is comparable with a centralized system.

The article is organized as follows: in Sec. 2 the nomadic approach is presented in terms of architecture and protocols. In Sec. 3 results of simulations are showed. Finally, in Sec 4 some conclusions and future research directions are presented.

2 Nomadic Wireless Sensor Network Architecture and Protocols

In the near future, it is reasonable to expect the surrounding ambient to be equipped with a halo of small tiny devices with sensing functionalities, and limited communication capabilities. These devices will be able to identify objects (RFIDs), or to measure physical phenomena surrounding us (sensors). As opposed to these embedded devices, there will be user devices, which will be constantly increasing in their communication, storage and processing capabilities.

The described scenario suggests a multi-tier network architecture. This direction was followed in [3], where it was shown that, by exploiting the users' physical mobility, it was possible to efficiently diffuse the information in an urban environment without the support of any backbone. Following a similar approach, we propose the Nomadic Wireless Sensor Network (NWSN) in order to maximally exploit the peculiarities of future pervasive environments and of the devices that will be composing them.

In the following the network architecture, and the related protocols, are detailed.

2.1 NWSN Network Architecture

NWSN try to fit its network architecture into the technological trend of extremely simple devices as opposed to particularly powerful ones. It is therefore assumed a hierarchical architecture with two kind of nodes:

- *sensor nodes*, which will be simple tiny nodes deployed in the environment, with limited functionalities of sensing and communication. We expect these nodes to be extremely low power and to run extremely simple communication protocols. The unique role of these devices will be the broadcasting of the sensed information to user nodes in the near proximity. As opposed to traditional Wireless Sensor Networks [8], we are freeing these nodes from the burden of running store-and-forward policies. Their network address might simply be their geographical location (e.g., GPS position), or identification number;

- *user nodes*, which correspond to users devices (e.g., PDAs, cell phones etc.). We assume these nodes to be capable of intensive processing operations, and of running complex information exchange protocols. These nodes will be moving in the environment as a consequence of the physical mobility of users, and will collect information from sensor nodes, when in their communication range, and store this information in their device's memory.
  User nodes will exchange the collected sensor information with other users encountered on-the-move. The exchange of the information will occur through single-hop broadcast.

The basic NWSN network architecture does not suppose any connection to the backbone, since it is expected that all the useful information, needed for running services on top of the NWSN, will be available from a nearby sensor or from user nodes encountered while moving.

Two user nodes, when in the communication range, will *opportunistically* exchange the information gathered from the environment.

2.2 NWSN Communication Protocols

As emerged from the NWSN architecture, there are two possible communications: user-to-user and sensor-to-user.

Information circulating in NWSN is expected to be always localized in time and space, meaning that the information, whenever is gathered from the environment, will be stored in the user devices together with the *age*, representing the time elapsed from reading of the sensor[1], and with a geographical position (e.g., GPS position)[2]. Hence, the smallest information unit exchanged from the user nodes will be a tuple $< value : age : location >$.

The sensor-to-user communication will be "one shot", where the sensor source broadcasts a single packet to mobile users in the communication range. The packet will consist of the tuple described above, where value is read in real-time through the sensing functionalities of the node. The user node stores the received information in the internal memory of the device in an ordered data structure, where the order may be time-based or location-based.

The user-to-user communication will contribute to the diffusion of the information gathered from the environment (e.g., the sensor sources), and physically transported by the user devices. This communication follows a simple handshake:

- user 1 sends a request for interest (RFI) packet to user 2. This packet contains some metric resembling the sensor data a user is transporting, i.e., the mean age and location of the information gathered from the sensor nodes;

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[1] We are not assuming, in principle, all nodes to be synchronized to a common clock. Indeed, we assume that when a sensor reading is relayed from a node to a new one, the node increases the age field of the tuple with the time the reading was stored in his device's memory.

[2] We can safely assume the GPS position to be set in the device at installation time, or to correspond to the mobile user position.

- user 2 receives the packet and decides whether he is in interested in the information that the second user is transporting. If so, user 2 sends a request for data (RFD) packet to user 1. If not, the communication between the 2 users ends;
- user 1, if a RFD packet is received, sends a bundle of information, containing the sensor data gathered from the environment.

Clearly, this will entail an exponential growth of the data exchanged as the number of sensor grows, and, thus, a mechanism to drop out the outdated information is also needed. We call this mechanism *Information filtering* and represents the policy, according to which information is discarded from the mobile users. User 2, when receiving the bundle of information, will merge the received data with his own. This is done by means of *Information Filtering* policies, where the information locality is exploited in order to drop data, which is considered as useless to the user, and merge the received useful information with the information already present in user 1 device's memory. Filtering can be done on a "bundle basis", or on an information data unit basis. In both cases, the information filtering policy, which determines whether to drop or merge the received information, will be in the form:

$$F(Age, Distance) < ServiceThreshold \tag{1}$$

where *Age* is the age of the sensor information, *Distance* is the user distance from the sensor source (the sensor node) and *Service Threshold* is a parameter that depends from the specific service constraints, and determines whether the information is useful or not to the user. In case filtering is done on a bundle basis, Time and Distance are the average age and distance of the sensor data units within the bundle.

It assumed that the services running on top of the NWSN will determine the Information Filtering policies, and that services will have a specific tolerance to delays of the sensor information exchanged. Hence, the service tolerance to delays will determine the specific values of the Service Threshold.

3 Simulation Environment

As a show case of the potential performance of the NWSN network architecture we choose a *parking lot finding system*, which is supposed to assist drivers in the search of a free parking spot in a city, suggesting the best destination according to its knowledge and, eventually, updating the destination of the users if better information is received on the way.

The aim of the simulation is to evaluate the performance of the parking lot finding service running on top of the NWSN network architecture, and to compare it when run on a centralized system. Hence, in this preliminary work, a simplistic model is assumed for the NWSN communication protocols and for the resources allocation, while the focus is on the number and speed of users needed for efficiently run such a service.

The model has been simulated in the freely available tool Omnet++ [9].

3.1 Parking Lot Finding System Application

We assumed each parking spot of the city to be equipped with a sensor, and the city to be uniformly divided in blocks. Users drive randomly around the city and, after a random driving time, decide to look for a free parking spot in a random block of the city. This would correspond to, let's say, "look for a parking spot near the train station" or "look for a parking spot near the theater".

The *parking lot finding system* assists drivers in the search of the free parking spot in the destination block, suggesting the destination that most likely will be free and, eventually, updating the suggested destination on the way, if more updated information is retrieved.

Due to simulation's scalability problems, we assumed two classes of users to be driving in the environment:

- *served users*, which correspond to users assisted by the parking lot finding service, thus benefiting from the system assistance in the search of a free parking spot;
- *unserved users*, which correspond to users not assisted by the service, thus transparently occupying parking spots for a random *ParkingTime* and leaving the parking unoccupied for a random *FreeTime*. The unserved users model is depicted in Figure 1.

Unserved users will keep occupying and freeing parking spots, and the less is the FreeTime, the less is the probability to find a free parking spot for the served users.

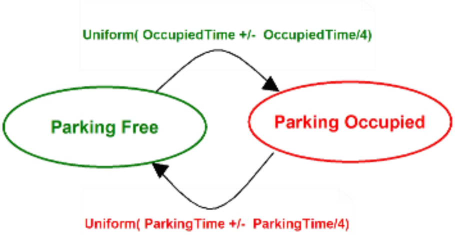

Fig. 1. Unserved users parking occupation model

The same service has been evaluated on the NWSN, on a centralized system, and compared also with the case of a random search, where no support is provided to the users in the search of a free parking spot.

In the following, the three simulated models are described. Please refer to [10] for more detailed description of the three simulated models.

Random Search Model. In the *random search model* it is assumed that mobile users nodes do not have any assistance in the search of a free parking spot, and they behave according to the following steps:

- move randomly in the playground size for a random driving time *DrivingTime*;
- decide to park in a random block k;
- move in block k, and, once entering it, start to move randomly as long as they do not find a free parking spot on their way. It is assumed that users are not aloud to leave the destination block before having parked;
- once parked, sleep for a random parking time *ParkingTime* and then starts from the first step again.

Centralized Network Model. In the *centralized network model*, we tried to imagine the way we would run the same parking lot finding system utilizing state-of-the-art technology. We assumed the network to be organized according to a 3-tier hierarchical architecture, as shown in Figure 2, with 4 kinds of nodes: sensor nodes, sink nodes, user nodes and a central control node.

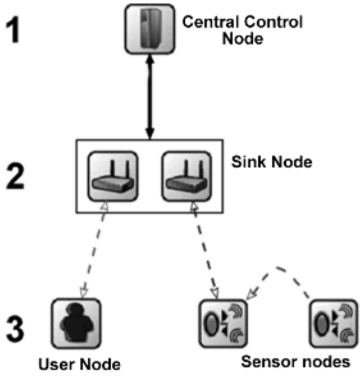

Fig. 2. Centralized model network architecture

Sensor nodes are deployed on every parking spot of the city. They sense the presence of a car, and transmit the change of their status to the nearest sink node in a multi-hop fashion. Routing is done according to the AODV [11] protocol. Clearly, there are several other routing protocols that are more efficient for a WSN, but the aim of this work is not to analyze the efficiency of the network, but rather to compare the performance of the service in the case of different communication paradigms.

Sink nodes are supposed to communicate with sensors for gathering the information on the parking lots status, with the central control for updating a centralized controller, and with the user nodes for answering to their service requests.

Central control node is the network node with a global knowledge of the parking spots status of the city. On the central control node resides the parking spot finding service, and mobile users, when looking for a free parking spot, send requests to this node, which answers with the best available destination. The available destination is simply the nearest free parking spot to the mobile user sending the request.

User nodes correspond to mobile nodes, randomly searching for a free parking spot. Hence, they will be able to communicate with the sink nodes, for sending requests to the Central control node, and for receiving answers from it.
Users behave according to the following steps:

- move randomly in the playground size for a random driving time *DrivingTime*;
- decide to park in a random block k, and, therefore, query the central control for the best parking, according to its knowledge;
- move towards the destination suggested from the central control, and update the destination on the basis of possible updates from the central control;
- once parked, sleeps for a random parking time *ParkingTime* and then starts again from the first step.

The central control node implements a virtual reservation mechanism. When a mobile user sends a request for a free parking spot in a block, the central control answers with the best destination available and virtually reserves this destination for other users searching in the same block. This is introduced in order to avoid the central control node sending several mobile users to the same destination.

Nomadic Wireless Sensor Network Model. The *NWSN model* is based on the Nomadic Wireless Sensor Network, as described in section 2.

Information gathered from the sensors is stored in an array of data, where each entry contains the reading and location of the sensor and the timestamp of the reading.

Without loosing in generality, in this first implementation we assumed the mobile users to be periodically sending a beacon message, for detecting other mobile users in the communication range. When a beacon message is received, the total information carried by mobile users is broadcasted.

The Information Filtering process consists of a simple time-based merge of the information received with the information carried: older information is dropped, while fresher information is kept. This is the simplest policy we can think at, and it unrealistically assumes infinite resources in the user device, i.e. it is possible to store one entry for every sensor node. Nonetheless, in this work we wanted to study if a totally distributed approach, such as the one NWSN, can yield to a system performance comparable to a centralized system, which has been considered as the optimal. Current work is dealing with a more accurate characterization of the Information Filtering and of the allocated resources.

Each user behaves according to the following steps:

- moves randomly in the playground size for a random driving time *DrivingTime*;

- decides to park in a random block k, and, on the basis of the knowledge stored in his device, selects the best destination , which is the nearest free parking place to the user. The mobile then starts moving towards it;
- eventually updates the destination when exchanging information with other users;
- once parked, sleeps for a random parking time *ParkingTime* and then starts from the first step again.

3.2 Simulation Details

The simulation scenario consists of a 4000 m. x 4000 m. playground size, which represents the simulated “city”. It is adopted a Manhattan network, constituted by 13x13 streets, starting from 5 m. and ending to 3995 m.. Each street is 2 meters width and has 2 lanes, with two opposite directions. The city environment is subdivided into 16 blocks. Each block is 1000 m. width and 1000 m. height.

Sensors are uniformly distributed over the grid, with a distance of 50 m. among 2 of them, and a communication range of 50 m.. Totally there are 2028 sensor nodes.

Mobile users are moving over the manhattan network at a constant speed and according to a random waypoint mobility model [12], if they have a destination, or a random walk, if they do not have a destination.

Mobile Users implement an IEEE 802.11b-compliant PHY and MAC layer protocols [13, 14], with a communication range of 150 m..

According to the simulation scenario, mobile users will communicate only when meeting along the streets. The introduced parameters are the same for the three simulated models. Clearly, not all of them are completely realistic, but are consistent with the aim of this work.

Time to Park. The metric adopted for evaluating the system’s performance is the *Time to Park*, which represents the time, measured in seconds, needed for a user to find a free parking spot starting from the instant he enters the destination block (in each one of the three models we assume that a user is looking for a parking place in a specific block of the city). The Time to Park represents a metric that is independent from the position of the user when he decides to start looking for a parking spot.

3.3 Simulation Results

Simulations have been run varying the speed and the number of mobile users, and the FreeTime of the unserved users. Each one of these parameters has a different impact on the performance of the systems, even though they are strictly related.

In Figure 3 the three analyzed models are presented with 2 and 4 minutes FreeTime of the unserved users. Both the NWSN as well as the centralized system perform better than the random search. How it’s intuitively clear, the less is the sensor FreeTime, the more is the network supposed to react fast for updating the users with possible alternative destinations. This is shown in

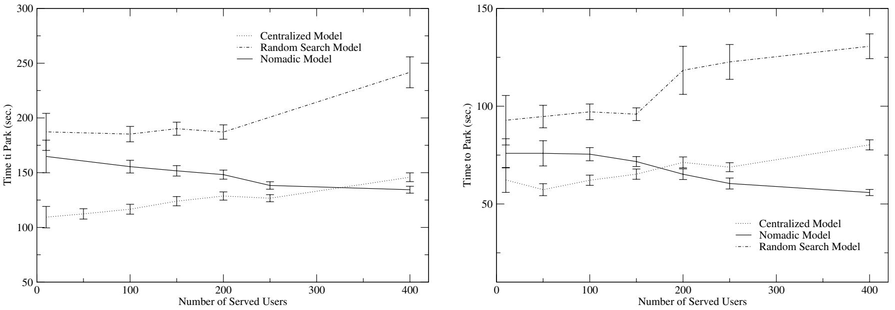

Fig. 3. Time to park in the case of a variable number of served users moving at a speed of 14 m/s speed, and with 2 min. (left) and 4 min. (right) freeTime of the unserved users

Figure 3, where, with 4 minutes of FreeTime all three models perform better than the case of 2 minutes FreeTime.

When comparing the three models, it is possible to see how with a number of served users high enough, i.e., around 300 with a 2 minutes $FreeTime$, and 400 with 4 minutes $FreeTime$, the NWSN system performs better then the centralized one. This is due to the effect of the virtual reservation mechanism implemented in the centralized model, which badly influence the assignment of free parking spots when the competition for the a free parking is extremely high.

While scaling the number of users, the random search and the centralized system decrease their performance due to a higher number of served users competing for the same free parking spots. Differently, the increased number of served users leads to more efficient diffusion of the information, and, thus, to a more stable performance of the service.

In Figure 4 the effect of the users speed (left graph) and the unserved users FreeTime (right graph) is analyzed in the case of 400 served users. As expected, the performance of the system increases with higher speeds. Nonetheless, above

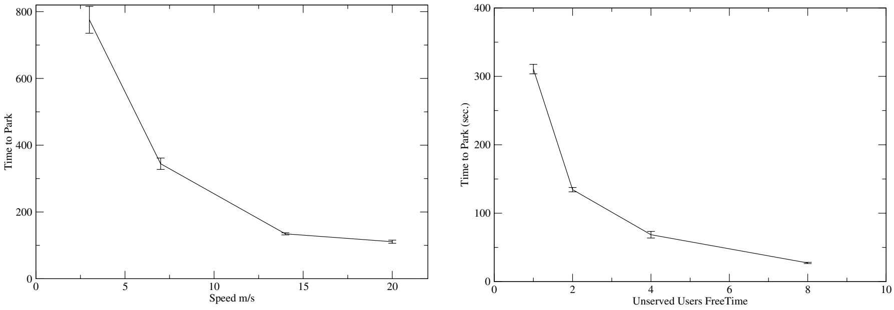

Fig. 4. Time to park in the case of 400 served users and a variable speed of the unserved users (left), and a different FreeTime of the unserved users (rigth) running the NWSN model

a certain threshold (e.g., 15 m/s) further increases in the users speed does not correspond to a similar improvement in the system's performance. A lower Free-Time corresponds to a sensor source changing faster in time, thus requiring the system to spread extremely fast the information in the network for having a good performance of the parking finding system. It is possible to observe that for a sensor source changing slower then 3 minutes does not seem to be a correspondent increase in the performance of the system.

4 Conclusions and Future Work

This paper presents the Nomadic Wireless Sensor Network, which is a communication paradigm specifically tailored to future pervasive environments.

The new challenges deriving from future ubiquitous environments are first introduced and described. The NWSN network architecture, and related protocols, are then introduced and evaluated in a specific case study: a parking lot finding system. The NWSN communication model has been evaluated and compared with the case of a centralized system. Simulations show how the NWSN, despite its simplicity, can perform as well as a centralized system, if an adequate number and mobility of the users are present.

Future work will be devoted to the evaluation of specific communication protocols. This will be reflected in a more fair and realistic utilization of the system resources. An analytical framework for the analysis of the Information Filtering will also be developed.

Finally, we are also working in the implementation of an experimental set-up of the system, in order to have an on-the-field assessment of the expected performances.

References

1. J. M. Kahn, R. H. Katz, and K. S. J. Pister, “Next century challenges: Mobile networking for ”smart dust”,” in *Proc. of ACM MobiCom*, Seattle, 1999, pp. 271–278.
2. M. Weiser, “The computer for the 21st century,” *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 3, no. 3, pp. 3–11, 1999.
3. I. Carreras, I. Chlamtac, H. Woesner, and H. Zhang, “Nomadic sensor networks,” in *Proc. of EWSN*. Istanbul, Turkey: Springer-Verlag, Jan. 2005, pp. 166–176.
4. I. S. S. Zhao, K. Tepe and D. Raychaudhuri, “Routing protocols for self-organizing hierarchical ad-hoc wireless networks,” in *Proc. of IEEE Sarnoff 2003 Symposium*, March 2003, pp. 65–68.
5. S. J. R.C. Shah, S. Roy and W. Brunette, “Data mules: modeling a three-tier architecture for sparse sensor networks,” in *Proc. of the IEEE SNPA*, May 2003, pp. 30–41.
6. L. Tong, Q. Zhao, and S. Adireddy, “Sensor networks with mobile agents,” in *MILCOM 2003 - IEEE Military Communications Conference*, October 2003, pp. 688–693.
7. K. Fall, “A delay-tolerant network architecture for challenged internets,” in *Proc. of ACM SIGCOMM 2003*, August 2003.

8. I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” *Computer Networks*, vol. 38, pp. 393–422, 2002.
9. OMNeT++ discrete event simulation system. [Online]. Available: http://www.omnetpp.org
10. I. Carreras, “Nomadic wireless sensor network: a parking lot finding system example,” CREATE-NET, Tech. Rep. 3, 2005.
11. C. E. Perkins and E. M. Royer, “Ad-hoc on-demand distance vector routing,” in *WMCSA ’99: Proceedings of the Second IEEE Workshop on Mobile Computer Systems and Applications.* Washington, DC, USA: IEEE Computer Society, 1999, p. 90.
12. J. Yoon, M. Liu, and B. Noble, “Sound mobility models,” in *Proc. of ACM MobiCom*, San Diego, CA, 2003.
13. *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std., Aug 1999.
14. *Supplement to 802.11-1999, Wireless LAN MAC and PHY specifications: Higher Speed Physical Layer (PHY) extension in the 2.4 GHz band*, IEEE Std., Sep 1999.