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State of the art of research on opportunistic networks, and definition of a common framework for reference models and performance metrics

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Participating institutions: ISMB, Bilkent/KHAS, NKUA/IASA, CNIT-CT, CNIT-BO, CNIT-TO, CNIT-PD, UPC, CNRS/LIP6, RWTH, CHAL/KAU, IST-TUL, TUM.
Contributors: R. Scopigno, M. Spirito (ISMB); I. Korpeoglu, A. R. Ulucinar (Bilkent/KHAS); A. L. Moustakas (NKUA/IASA); L. Galluccio, A. Leonardi (CNIT-CT); F. Fabbri, R. Verdone (CNIT-BO); C.F. Chiasserini (CNIT-TO); A. Zanella, F. Zorzi (CNIT-PD); R. Ferrus, F. Novillo (UPC); M. Boc, M. Dias de Amorim (CNRS/LIP6); J. Riihijarvi (RWTH); A. Brunstrom, M. Cavalcanti de Castro (CHAL/KAU); L.D. Pedrosa (IST-TUL); D. Traskov (TUM).
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Abstract:
This deliverable reports the state of the art of research on Opportunistic Networks together with the definition of a common framework for reference models and performance metrics inside WPR11 of NEWCOM++. Moreover, the deliverable proposes the main research issues on opportunistic networks to be investigated, and presents several planned Joint Research Activities (JRAs) which will be pursued in the course of the WPR11.

Keyword list: opportunistic networking, delay tolerant networks, mobility, routing, resources allocation, joint research activities.

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1 INTRODUCTION

NEWCOM++ WPR11 addresses the emerging paradigm of opportunistic communication, which enables nodes and user devices to self-configure and exploit resources in extremely dynamic networks. This paradigm encompasses features and methods that are especially suitable in both disconnected environments, in which islands of connected devices suddenly appear, disappear and reconfigure dynamically, and pervasive networking scenarios, where epidemic data exchanges occur among mobile devices in temporary proximity.

The present deliverable, DR11.1, aims at providing an overview of the current state of the art of research on opportunistic networks and definition of a common framework for reference models and performance metrics.

More specifically, we start by a taxonomy of opportunistic networks, reviewing the definitions already known in literature, and we show the most relevant opportunistic networking applications.

Next, we provide some details on the architecture, characteristics and requirements of opportunistic networks. We also describe the performance metrics of interest, the reference network scenarios and some tools that can be used to study the performance of opportunistic networks.

In the following section, we focus on the main research issues in opportunistic networks. We begin discussing challenges and possible solutions regarding mobility characterization and discovery algorithms. We then consider existing results on routing and forwarding techniques for opportunistic networks. We conclude the section by discussing novel scheduling, resource allocation and MAC schemes.

Next we proceed to describe the Joint Research Activities (JRAs) that have been defined in the context of WPR11. For each JRA, we provide the participating institutions, the definition, open issues and goals, and the work organisation if already defined.

The document is organized according to the task organization reported in the NEWCOM++ Annex I. In particular, three tasks have been identified: Task TR11.1, "Properties and requirements of opportunistic networks", which corresponds to Section 3 of the present Deliverable; Task TR11.2, "Resource management issues in opportunistic networks", which corresponds to Section 4.3; and Task TR11.3, "Routing/forwarding schemes for opportunistic networks", which is related to Section 4.2.

1.1 List of Acronyms

AP	Access Point
CAN	Content Addressable Network
CAR	Context-Aware Routing
CP	Concentration Point
CSMA	Carrier Sense Multiple Access
DHT	Distributed Hash table
DTN	Delay Tolerant Network
GPS	Global Positioning System
GSM	Global System for Mobile communications
HW	HardWare
MAC	Medium Access Control
MANET	Mobile Ad hoc NETworks
MAP	Mobile Access Point
MBR	Model Based Routing
MEMS	Micro Electro-Mechanical Systems
MF	Message Ferrying
MPLS	Multi Protocol Label Switching
MV	Meetings and Visits
OLSR	Optimized Link State Routing
OSA	Opportunistic Spectrum Access
P2P	peer-to-peer
PC	Personal Computer
PDA	Personal Digital Assistant
PSN	Pocket Switched Networks
RF	Radio Frequency
RFID	Radio Frequency IDentification
RR	Radio Resource
RRM	Radio Resource Management
RU	Radio resource Unit
RWP	Random Waypoint
SW	SoftWare
UMTS	Universal Mobile Telecommunications System
UWB	Ultra Wide Band
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VANET	Vehicular Ad hoc NETworks
VoIP	Voice over Internet Protocol
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMN	Wireless Mesh Networks

2 TAXONOMY OF OPPORTUNISTIC NETWORKS

In this Section we provide the definition(s) of opportunistic networks already known in literature and we discuss the most representative opportunistic networking applications.

Opportunism in wireless networks is a very recent concept, aiming at jointly exploiting the resources of separate networks according to the needs of specific application tasks.

Actually, such concept is getting a growing attention in the latest literature even though it is used by different authors with slightly different meanings. In particular, two main research trends appear to be the most relevant:

1. A peculiar type of network opportunism has been recently investigated by some authors and it is related to the so-called Delay Tolerant Networks (DTNs).

2. Lilien et al. [1] presented a novel paradigm of opportunistic networks in the context of Emergency Preparedness and Response [2], also called *oppnets*.

Below we report some examples of applications related to the two research trends.

2.1 Delay Tolerant Networks

A *Delay Tolerant Network* (DTN) is defined as a network of *regional networks*. A regional network is a network which relies on its own protocol stack, consequently, all the nodes of the regional network use the same type of communication mechanism [3, 4, 5, 6, 7]. A DTN is an overlay which supports the interoperability of regional networks which may be characterized by one or more of the following characteristics:

- Intermittent Connectivity
- Long or variable delay
- Asymmetric data rate
- High error rate.

Examples of these challenged networks include [8]:

- *Terrestrial Mobile Networks*. Some of these networks may become unexpectedly partitioned due to node mobility or changes in signal strength, while others may be partitioned in a predictable manner.
- *Non-conventional Media Networks*. They include near-Earth satellite communications, deep space communications, acoustic links in air or water. These systems may be subject to high latencies with predictable interruptions.
- *Tactical Ad Hoc Networks*. These systems can operate in hostile environment where different factors may be cause for disconnections.
- *Sensor/Actuator Networks*. Here the intermittent behavior is given by the periodic active/sleep state of nodes, rather than by their mobility.

The overlay network which characterizes the DTN architecture has the task to act as a Gateway to allow the communication between different types of networks. In particular, a DTN may support different wireless technologies including radio frequency (RF), ultra-wide band (UWB), free-space optical and acoustic (sonar and ultrasonar) technologies.

The characteristics of DTNs are clearly different from the common networks where we assume that there is a continuous and bidirectional path between the source and destinations with reliable and fast symmetric links.

Instead, in a DTN we need a mechanism which allows to move a message from a storage place to another storage place, along a path that we suppose reaches the destination. This mechanism is called the store-carry-forward mechanism because if a message cannot be delivered immediately, each node in the network holds the message indefinitely and waits for future contact opportunities with other devices to forward the message. Obviously, the best carriers are those having the highest chance of successful delivery.

The most representative opportunistic networking applications, which fall under the research trend of Delay Tolerant Networks, are:

- Pocket Switched Networks (PSNs)
- Autonomic Networks
- Socio-Aware Community Networks.

2.1.1 Pocket Switched Networks

We define the Pocket Switched Networks (PSNs) as a communication paradigm that relies on both occasional transmission opportunities and user mobility to carry the data to the destination.

The purpose of this communication paradigm is to reflect the reality faced by the mobile users [9]. A mobile user is someone who owns a mobile communication device which has one or more wireless interfaces. In order to fully exploit the wireless connectivity (like e-mail, Web, etc.) a mobile device must be connected to an access point that is not always available. When the access point is not available, a large amount of wireless bandwidth capacity remains unused. We suppose that in a mobile environment, there are many mobile devices that are often in the same range so they can interact. The idea behind the PSN is to use the intermittent connectivity between two or more mobile devices.

This type of networks rely on the following assumptions:

- Mobile networking users carry one or more devices having significant *storage capacity*.
- Their mobility may be useful as a *data-carrying mechanism*.
- Devices have local networking interfaces, with which they can exchange data with neighbors.
- Devices may have access to one or more global networks (e.g., Internet, GSM), which differ in price, bandwidth, and availability.
- Both global and local connections may provide *opportunities to transfer data*.

A Pocket Switched Network can be considered a specific application domain of Delay Tolerant Network but it has a different approach. In particular, the aim of PSN is not to extend the Internet legacy applications to support an intermittent connected communication environment, but it is a new communication architecture that can use the Internet or other type of local communications when they are available.

In order to successfully implement the PSN communication paradigm we must identify the challenges to be addressed.

- *Usability*:
  - It is needed to provide some level of predictability regarding the behavior of PSN.
  - It is needed to provide an appropriate feedback to users about the state of the system.
- *Naming*. Naming provides *indirection* and a way to identify things. Name construction can be an emergent property of the node behavior or state.

- *Security*. A number of resources may be at risk, there is the need for security.
- *Forwarding*. Which node is more likely to forward the message? How is it possible to select the best relay?
- *Mobility*. The wireless technology should be designed for short-lived connection opportunities between power-limited devices.
- *Resource Management*. A trade-off between energy conservation and network management should be found.

2.1.2 Autonomic Networks

Autonomic Networking is a network paradigm that has the purpose to create self-managing networks to overcome the rapidly growing complexity of the Internet and other networks and to enable their further growth, far beyond the size of today [10]. The main problem of the Internet is an architectural problem. The Internet architecture is not ready to integrate and manage the envisaged huge numbers of dynamically attached devices (wireless revolution, mobility, personal area networks etc.) and it lacks of integrated monitoring and security mechanisms. For this reason, a new architecture is needed to federate multiple heterogeneous networks.

The interconnection of different types of networks is a concept that it is possible to find into the DTN architecture, but the Autonomic Networking is focused to interconnect the different types of networks (regions) in automatic way, without requiring active human intervention. In particular, the flexible architecture allows a simple way to implement a network that tolerates the delay and that supports the intermittent connectivity.

The main implementation of such paradigm can be found into the *Autonomic Network Architecture* Project (ANA Project) [11]. In particular, the challenges of the ANA Project are:

- Networking challenges:
  - Interconnection between heterogeneous networks.
  - Network design with flexible compartments.
  - Routing between networks compartments (instead of hierarchical routing).
  - Autonomic features for network management [10] [12].
- Node design challenges:
  - Flexible layer compartments instead of static layers.
  - Support for network monitoring.
  - Functional composition of networks services.
  - Multiple node compartments that can run in parallel.

Autonomic characteristics can dramatically improve the efficiency of opportunistic communications [13]. In this field, the Haggle Project [14], proposes a communication architecture that provides autonomic and opportunistic communication services to mobile end-points which are intermittently in reach of other devices or networks.

2.1.3 Socio-Aware Community Networks

Socio-Aware Networking is a paradigm focused on human-to-human communications. The human interactions present a series of challenges that should be taken into account. The first problem is related to the particular type of connectivity between two or more humans. The other aspect regards the mobility.

Consequently, to cope with human networking, both a networking paradigm supporting the intermittent connectivity and a social mobility model for evaluating the human behavior are needed.

To address the intermittent connectivity in human networks, it is possible to adopt the DTNs paradigm which supports the message delivery without an already established end-to-end path between the sender and the receiver, as already shown above. Concerning the social mobility model, a key requirements is capturing trace data from the real world in order to construct realistic synthetic models. To this purpose, the Crawdad database [15] provides extensive traces including location information and node connectivity information.

An interesting approach is proposed in [16]. Authors provide an overlay for supporting a Publish/Subscribe Communication over DTNs where human behavior exhibits the characteristics of networks by forming a community. This overlay is based on the data dissemination through a gossiping approach.

In particular, the overlay network in [16] proposes a Publish/Subscribe mechanism for supporting a many-to-many communication type. The Publish/Subscribe approach provides several benefits. The main benefits come from the message-based communication that allows to find data through their content. This approach allows a decoupling between data and data providers. The decoupling is in space because there are no connections between clients, in flow because no synchronized operation is required on event publishing and subscribing, and in time because the clients are not required to run at the same time.

The Publish/Subscribe overlay is also based on three classical actors that are: the publisher, the subscriber and the broker. In particular, the network is divided into different community. A community is a group of connected nodes in which the members are likely to share the same interest. There is one broker for each community and the broker can be connected to other brokers to form an overlay network composed by brokers of each community and the associated publishers. In this overlay network the broker can exchange information. The communication between the broker is based on data dissemination techniques.

2.2 Oppnets

Oppnets constitute the category of ad hoc networks where diverse systems, not originally employed as nodes of an oppnet, join it dynamically in order to perform certain tasks they have been called to participate in.

Oppnets differ from traditional networks, in which the nodes of a single network are all deployed together, with the size of the network and locations of its nodes pre-designed. In oppnets, the initial *seed oppnet* grows into an *expanded oppnet* by taking in foreign nodes. In other words, diverse devices join the original set of seed nodes to help the oppnet realize its goals and are so called *helpers*. In fact, it might happen that the resources available in the seed oppnet are not sufficient to accomplish the task; in such situation, the network can try to scan the radio environment, detect the presence of other networks deployed for different tasks (e.g. WiFi hot spots, or computer networks in an office environment, or GSM/UMTS public networks) and address such helper networks trying to exploit their available resources.

Oppnets might be perceived as networks that lie within the intersection of ad hoc networks, P2P systems, and sensor networks. Concerning the range of applications for Oppnets, [17], they can be used for Emergency situations and homeland security. In predictable disasters (e.g. hurricanes), seed nodes can be put into action before the disaster when it is much easier to locate and invite other nodes. For example, the first invited helpers could be the sensor nodes deployed for monitoring buildings, roads, etc.

Moreover, a seed oppnet might be deployed in the area where an earthquake occurred. It is an ad hoc wireless network with nodes much more powerful than in a *typical* ad hoc network (more energy, computing and communication resources). Once activated, the seed tries to detect any nodes that can help in damage assessment and disaster recovery. In emergency situations, entities with any sensing capabilities (whether members of sensornets or not), such as cellphones with GPS or desktops equipped with surveillance cameras, can be especially valuable for the oppnet. Let us suppose that the oppnet is able to contact three independent sensornets in the disaster area, deployed for weather monitoring, water infrastructure control, and public space surveillance. They become helper candidates and are ordered to immediately abandon their normal daily functions and start assisting in performing disaster recovery actions. For example, the weather monitoring sensornet can be called upon to sense fires and flooding, the water infrastructure sensornet with multisensor capabilities (and positioned under road surfaces) sense vehicular movement and traffic jams, and the public space surveillance sensornet automatically search public spaces for images of human victims.

2.3 Discussion

According to the classification into the two main research trends it is possible to identify the main research issues to be investigated.

In particular, concerning the research trend close to the Delay Tolerant Networks paradigm, which is the most common definition in literature, the main issue to be investigated is the routing approach. This topic will be discussed in Section 4.2.

Instead, concerning the opportunism which falls under *oppnets* the main research challenge regards the discovery of resources. This will be investigated in details in Section 4.3.

3 Properties and Requirements of Opportunistic Networks

In this Section, we provide some details on the architecture, characteristics and requirements of opportunistic networks. We also describe the performance metrics of interest, the reference network scenarios and some tools that can be used to study the performance of opportunistic networks.

3.1 Network Architecture

In an opportunistic environment, nodes are typically mobile (e.g., pedestrian users or vehicles), although some fixed nodes may be present as well. Nodes can discover each other and communicate by using all kinds of communication media, including Bluetooth, WiFi, RFID, cellular-based technologies, etc. Also, some of them may act as point of access toward the fixed Internet or a satellite link [18].

The network is typically separated into several network partitions, called regions; as a consequence, an end-to-end path between the source and the destination may never exist. Furthermore, the link performance is typically highly variable or extreme, and, thus, even if there is an end-to-end path between the source and the destination, it may last only for a brief and unpredictable period of time.

To solve this issue, node mobility and local forwarding can be exploited for data transferring: the network nodes can store and carry data around while they are moving, and then forward the data during opportunistic contacts. During these opportunistic contacts, entire chunks of a message can be transferred from one storage place to a storage place in another node. It follows that nodes may transfer data to the destination either through single-hop transmissions or using the multihop paradigm (i.e., along a path that is expected to reach the destination).

The intermediate nodes between a source and a destination implement the store-carry-forward message switching mechanism, by overlaying a new protocol layer, called the bundle layer, on top of heterogeneous region-specific lower layers [19, 20]. Thus, in an opportunistic network, each node is an entity with a bundle layer which can act as a host, a router or a gateway. When the node acts as a router, the bundle layer can store, carry and forward the entire bundles (or bundle fragments) between the nodes in the same region. On the other hand, the bundle layer of a gateway is used to transfer messages across different regions. A gateway can forward bundles between two or more regions and may optionally be a host, so it must have persistent storage and support custody transfers.

3.2 Characteristics and Requirements of Opportunistic Networks

In an opportunistic network, whenever nodes move away or turn off their power to conserve energy, links may be disrupted or shut down periodically. These events result in intermittent connectivity. When there is no path existing between the source and the destination, a network partition occurs and nodes need to communicate with each other via opportunistic contacts through store-carry-forward operations.

In such a context, the following aspects are therefore of particular importance: the contact opportunity, the node storage, and the node willingness to cooperate.

- *Contact opportunity:* Due to the node mobility or the dynamics of the wireless channel, a node might make contact with other nodes at an unpredicted time. Since contacts between nodes are hardly predictable, they must be exploited opportunistically for exchanging messages between some nodes that can move between remote fragments of the network. In addition, the contact capacity needs to be considered, i.e., in other words, how much data can be transferred between two nodes when they are in contact with each other.

- *Storage constraints:* As described above, to avoid dropping packets, the intermediate nodes are required to have enough storage to store all messages for an unpredictable period of time until next contact occurs. In other words, the required storage space increases as a function of the number of messages in the network. Therefore, the routing and replication strategies must take the storage constraint into consideration. If the node storage capabilities are limited, a buffer-management (i.e., data drop) strategy must be implemented [21].

- *Cooperation level:* In many cases, in opportunistic networks nodes may be required to provide their own resources (e.g., memory, bandwidth, battery power) for others to use, without getting any direct benefit from that. A strategy based on reciprocal altruism (also said Tit-for-Tat) may be not sufficient to guarantee cooperation, especially in a mobile environment, where also observations on the node behavior may be affected by errors.

3.3 Performance Evaluation

Below, we report some metrics of interest, that can be used to characterize opportunistic networks and assess their performance. We also list some models and tools that can be used to represent opportunistic network scenarios.

3.3.1 Characterizing the User behavior and the Network Topology

Consider that the generic network node has a radio range equal to r. We introduce the following metrics [22]:

- *Contact time:* The time interval during which two users are in each other's communication range.
- *Inter-contact time:* The time interval between two contact periods of a pair of users.
- *First contact time:* The waiting time for a user to contact its first neighbor (ever).
- *Node degree:* The number of neighbors of a user.
- *Network diameter:* The longest shortest path of the largest connected component of the communication network formed by the users.
- *Clustering coefficient:* Given a user, it is the proportion of links between the user within its neighborhood divided by the number of links that could possibly exist between them.
- *Travel length:* The distance covered from when a user logins to the time instant when it logouts.
- *Effective travel time:* The total time spent while moving (thus, it does not include pause times).
- *Travel time:* The total connection time of a user.
- *Zone occupation:* Consider the whole network area divided into zones, the zone occupation is the number of users in every zone.

3.3.2 Assessing the Network Performance

To evaluate the performance of algorithms and protocols designed for opportunistic networks, the following metrics can be considered:

- *Packet delivery ratio:* The number of successfully delivered packets divided the total number of transmitted packets.
- *Message delivery ratio:* The number of completed messages divided by the total number of transmitted messages.
- *Buffer occupancy:* Buffer occupancy at the network nodes.
- *Latency of a message:* The time between the instant that the message is generated at its source node and the time it is available at the destination node.
- *Packet duplication probability:* The probability that duplicated packets arrive at the destination.

- *Reliability* $\eta(t)$*:* The probability that a random message has a latency smaller than t.
- *Path length:* The number of hops through which a packet has to travel before reaching its destination.

3.4 Models and Tools

The following models and tools seem to be particularly suitable for representing the behavior of opportunistic networks:

- Models based on expectations of how mobility is performed in specific situations such as campus [23] and vehicular mobility models [24, 25].
- Models tweaking Random WayPoint (RWP) parameters with specific distributions in order to yield more realistic results [23, 26].
- Mobility measurements performed both indoor and outdoor [27, 28]. In particular, in the iMotes experiments [27], users carried Bluetooth enabled devices, which periodically recorded the presence of other Bluetooth-enabled devices, such as other iMotes, PDAs, mobile phones, or laptops. A contact situation between individuals was asserted as soon as the presence of one node was felt by the other one, and an inter-contact asserted as soon as two or more consecutive measures did not show the presence of a previously seen node. The UMassDieselNet dataset [29], instead, includes traces collected by considering 40 buses, each equipped with an IEEE 802.11.b communication device and running mainly over the UMASS campus area. These measurements enabled the proposal of trace-based models calibrated with empirical data [30, 31]. They also confirmed the presumption that RWP is unable to realistically model human mobility, since it leads to exponential distributions for both contact and inter-contact times. Furthermore, these studies show that both contact and inter-contact distributions [27, 28], as well as location popularity distribution [30], follow power-law distributions.
- Mobility simulators, such as SIMPS [32]. SIMPS adopts a mobility modeling approach centered on human behavioral rules. Behavioral mobility models rely on continuously interacting rules that express atomic behaviors governing social mobility. In SIMPS, the following assumptions hold: (i) fixed social interaction need per individual and (ii) fixed social graph representing social ties between individuals. Hence, the need of social interactions is satisfied by either encountering acquaintances or escaping from non-acquaintances. This requires that individuals meet through spatial displacements, thus leading to mobility.
- Synthetic traces collected by using Second Life [22]. These traces provide similar results to those obtained in real-world experiments. From a qualitative point of view, user mobility in Second Life presents similar paths to those of real humans.

3.5 Reference network scenarios

Here we present some examples of opportunistic networks that can be taken as reference scenarios.

3.5.1 Indoor Scenarios

- *Dancing room:* People equipped with small communication devices, likely using short-range technologies such as Bluetooth. Users will be stationary or moving at walking speed, while the network topology may include several clusters. People will exchange short data files, videoclips, and images, but they may also need to send broadcast messages, such as requests for car pool services.

- *Conference room:* People attending a conference or a business meeting, each of them equipped with one or more communication devices. In this case, users are either stationary or moving at walking speed. Traffic will be mainly represents by data file and video contents.

3.5.2 Outdoor Scenarios

- *Mountain area:* Winter hiking and mountaineering are major sport activities attracting a large (and increasing) number of people. Many different social clusters of people may traverse it at any point in time (e.g., tour groups, alpine guards, alpine skiers etc). The ability to exploit the social nature of the ties between these people to create mobile pervasive networked environments is very important and may find many applications (information services, environmental monitoring, advertisements, safety services, etc.)
- *City center:* Urban centers, where both vehicles and people equipped with communication devices exchange information and ask for services, will be soon a reality in several countries. Possible services include taxi reservation, request for information on fast routes, events or point of interest. In addition, users may form virtual communities and share contents such as videoclips or data files.

4 Research Issues in Opportunistic Networks

In this Section we discuss the main research issues in opportunistic networks. Some of them have been identified during the WPR11 KO meeting held in Catania on March 13-14, 2008.

In particular, we discuss challenges and solutions for the following research fields:

- Mobility characterization and discovery algorithms.
- Routing/forwarding techniques.
- Novel scheduling, resource allocation, and MAC schemes.

4.1 Mobility characterization and discovery algorithms

It is possible to characterize nodes mobility as a function of several aspects, in fact, from everything that can be sensed. In networking, the analysis of spatial mobility (with the temporal aspect) has always had a great importance. Only recently, the study of contacts and inter-contacts between nodes has raised to another level with new paradigms in ad hoc networks (delay tolerant, opportunistics, etc.). The choice of the relevant aspects for analysis is mostly related to the environment of application. Generally, the analysis of spatial mobility allows to develop enhanced mobility models, improve location and mobility management, and to make mobility predictions. By considering contacts, it is mostly routing and forwarding protocols in infrastructure-less networks that we can setup and/or improve. In this document, we describe the state-of-the-art of the domain of mobility characterization by considering only the spatial aspect. Because it is still very difficult to characterize mobility according to how contacts occur, this aspect will be not treated. Finally, we discuss open issues in this domain.

4.1.1 Spatial mobility

The analysis of spatial mobility is a research subject that is relevant in a wide range of domains (populations migration, geographic information science, transportation, wireless networking, etc.). This analysis can be considered as useful to crucial depending on the degree of influence the simple variation of mobility patterns (or behaviors), even minor, can have on the studied system. Most of the time, the analysis of mobility characteristics is performed through the study of data traces resulting from the tracking of a certain number of nodes. According to the method used, the raw data traces can be treated as they have been obtained or, an intermediate level whose purpose is to hide tracking effects and to interpret the patterns of mobility can be alternatively used. In the following we first discuss the methods proposed to transform raw patterns into a succession of places and paths, then mobility models based on observed mobility characteristics.

4.1.1.1 Mobility patterns interpretation

If we consider both spatial and temporal aspects, it is commonly accepted that the finest granularity to characterize a mobility behavior is through "pause times" and "travel times" [33]. This raw distinction is interesting but extremely tough to handle, and leaves open a certain number of issues. Depending on the technology used to track a mobility pattern (GPS, succession of association, questionnaire, etc.), it can be difficult to detect the exact duration and position of all "pause times" and, if available, to attribute a meaning to each of them. It is then more "comfortable" to consider the mobility trajectory as composed by areas of pause times: "places" and a number of "paths" (≥ 0). A place is generally an area where the cumulated pause duration is long enough to be distinguished as important for the node. A path is a succession of movements between two places (or an outer loop on the same place).

The interest of treating the mobility of nodes as a succession of place(s) and path(s) is mainly to rationalize what we observe and then to give motivation(s) behind the movements. With this abstraction level, several studies have been performed to investigate, for instance, how routing takes place in daily mobility, the influence of visited places on the transportation mode choice, the analysis of cyclic aspects of mobility patterns, the production of mobility models.

The literature in the domain of places detection is rich of proposals [41, 39, 40, 42, 43, 44, 37, 38] (this is far to be an exhaustive list). As far as we know, all of these approaches use clustering methods to create places where raw location points - obtained under the form of coordinates in a metric system - are within a predefined radius or create a particularly dense area. The main variations between them are about the choice of the clustering algorithm and the technology used to obtain the visited locations (and then the accuracy level induced).

All proposed approaches related to places discovery start from a raw data input series $R = \{r_i\}$ which represent a set of pairs $r_i = (l_i, t_i)$ corresponding to a location l_i with its associated timestamp t_i. According to the technology used to obtain this raw series, important information such as durations of stay, distances, etc. will be naturally embedded or not. Most of the methods use coordinates in a metric space, as raw data input for locations.

Polled GPS data points have an accuracy level of about 10 meters, the signal drops in opaque buildings and the position acquisition latency can vary from seconds to minutes. In this context, Marmasse *et al.* in [39] use the signal dropout in opaque buildings characteristic as a base to define buildings that can be considered as a place for the node. If the node looses the GPS signal three times in a given radius around a last seen coordinate, the area contained in this radius is considered as a place. On the same basis, Ashbrook and Starner in [41], use this signal dropout effect to determine places. The idea, however, is first to consider a radius around a place point. All the points within this radius are considered to determine the mean, which will be the new center of the radius. This process is repeated until the center no longer moves. This strategy is designed to overcome the variation of GPS points obtained at same location. The authors also introduce the notion of sub locations with the same clustering strategy.

Another mean to determine the current location is by using Place Lab. It is a system that collects coordinates of access-points (APs), through war-driving (act of searching APs from a moving vehicle) for instance, and make them available on a distant server. With this technology, Kang and Welbourne in [40] propose a one pass clustering algorithm to determine places. The system gets the current coordinates at a rate of once per second by retrieving the coordinates of the APs' sensed beacons and by applying a centroid scheme. Their clustering strategy is to group location points that are within a radius around the first considered location. If the duration spent within this radius is greater than a time threshold, then the cluster is considered as a place.

In the two previous contexts, the duration of stay in one location was hidden behind the density of the measures taken at constant rate. Hence, the density of points can highlight the presence of an important place for the node. Because of the accuracy of the GPS data points, one way to delimit the perimeter of the place is to cluster the data points through geometrical areas around the density of points and/or the lack of measures (signal drop). Somehow, this idea of density of points has led Zhou *et al.* [42] to propose a modified density-based clustering algorithm, named DJ-cluster (Density and Join-based clustering) to group the data points in one-pass.

We can also consider that the location of a node cannot be determined periodically and only coordinates of APs are available. In [33], Kim *et al.* first get around the problem of obtaining a sequence of location points as close as the real physical mobility pattern of the node by using a Kalman filter. They then address the problem of retrieving the duration of stay by tacking into account the speed of transition between two APs. Considering a human speed and the distance between two APs, if the resulting speed is slower than an average walking speed for the distance then the user has made a pause. Because the user can change association without having moved (signal overlapping), they propose to cluster succession of pauses according to a distance threshold.

In [36], Hightower *et al.* propose to use sensed beacons if APs coordinates are not available. In their solution, BeaconPrint, the node listens to beacons during a duration (with a length to be considered as place) and, according to a confidence parameter which measures the stability of movements through the number of new beacons, decides if the node is in a place.

Finally, the work of Laasonen *et al* in [37] addresses the problematic of characterizing places considering only the nodes mobility at the topology level, here in a GSM-network. In their approach they apply two levels of clustering: The first level groups cells where the node undergoes oscillations (ping-pong effect) considering the durations of visit (which is spread between the cells) and by limiting the diameter to 2. The new graph is then considered as composed by “locations”. Significant locations (in terms of time spent) are considered as “bases” and a new weighted graph is generated. The weight for a link corresponds to the mean travel time between two bases. Finally, with a density-based clustering algorithm, bases are clustered in “areas” w.r.t a travel time threshold as distance metric.

The abovementioned approaches consider two important steps in places discovery. The first is to take into account the accuracy of the technology to group points that could have the same meaning for the node: two GPS polled points in the same location could produce two differents coordinates; at the same physical location, signal overlapping can cause the association on different cells (or APs). The second is to characterize the domain of influence of places between them: some use geometrical forms as circles, clusters merging, and/or duration of travel. These two levels are based on constraints defined *a priori*.

4.1.1.2 Mobility modeling

The analysis of mobility behaviors leads to the identification of major common characteristics with the purpose of proposing mobility models as close as possible to that observed in real data traces. In the domain of networking, several studies have been focused on the analysis of data traces that come from tracked devices in wireless local-area networks and in cellular networks.

In [45], Balazinska and Castro analyze the mobility behaviors of about 1366 users and 177 APs in a corporate campus WLAN. In their context, they found that the nodes activity follows office work hours with peaks around 12 and 4pm, and during workdays. This first observation is recurrent in almost all contexts where nodes tracking are performed in their environment of work. The opposite behavior is observed when nodes are tracked in their all mobility environment including home, dormitories, and metropolitan networks. The second observation is that a large fraction of nodes have a “home location” (a place where the user spend most of its time in the network) and a certain number of “guest locations”. Finally they introduce two metrics: (1) the prevalence (reflects the frequency with which users visit various locations. (2) The persistence (reflects session durations). Through the analysis of these two metrics, they showed that mobility behaviors are organized around home locations. This location is visited frequently and the durations of association are long, while guest locations are visited for short periods of time and infrequently.

These characteristics have also been observed by Henderson *et al.* in [48]. The environment of study is a compact campus composed by 188 buildings and 566 APs. Because they tracked nodes mobility in work places and in dormitories, they observe a larger fraction of nodes that had a home location. They also note that wireless devices that stay “always-on” such as VoIP devices and PDAs have wider mobility with much shorter session durations. Tuduce *et al.* in [46] proposed a mobility model based on the observed characteristics of mobile nodes in the same type of environment. The parameters they used for their model have been directly picked up from the real data traces. For the spatial aspect, they note that the probability a node will move to a neighboring place is about 30%, to the same place 36% and to a non-neighboring place 34%. They used the metric of prevalence proposed in [45] to determine a set of places a node must visit. For the temporal aspect, they choose a maximum movement speed at 3m/s and they make the sessions duration follow a general Pareto distribution with a shape parameter of 0.22 and a scale parameter of 0.15.

In the above-related analyses, different contexts bring almost identical characteristics. The two notions of home location and guest locations, and their ratio, can help characterize the type and the intensity of the mobility behaviors of the nodes. Balazinska and Castro proposed to categorize nodes into five groups with the help of the measures of prevalence and persistence: (1) stationary users, (2) occasionally mobile, (3) regular, (4) somewhat mobile, and (5) highly mobile.

By tracking nodes mobility according to a wireless network infrastructure, however, the analysis can be influenced by the relationship the nodes have with this infrastructure. By staying always-on, some tracked devices should better reflect the natural mobility of nodes in the studied environment.

Kim *et al.* in [33] also consider that the association pattern introduces a bias according to the real physical mobility of the node. They then developed a method, using a Kalman filter, to transform a raw data trace of sequence of associations in a trace of physical movements that reproduce pause times. For their mobility model, they choose to focus on hotspots (popular regions in the network) to represent the different destinations (waypoints). In [49], Sarafijanovic-Djukic *et al.* analyzed the mobility of approximately 825 taxis in the city of Warsaw, Poland during three months through GPS tracking. In their analysis they do not compare the above-mentioned characteristics (because of the lack of wireless infrastructure) but show that there exist some "concentration points" (dense areas where nodes will have higher probability to encounter other nodes) that are stable geographically and for long periods of time. This feature is interesting in the sense that we can now view the nodes mobility as a graph of concentration points (CP) independently of the underlying environment. When the node discovers a dense area of other nodes, there is a high probability that this area will last for weeks in the same physical location. A CP can then be considered as virtual place for the node.

To summarize, one approach to characterize the mobility of nodes in a context is first to detect places of interests (hotspots, concentration points, etc.) and to understand how a node moves between them. Another mean to characterize the mobility of the nodes is to consider the spatial aspect as constrained by the temporal aspect. By choosing different temporal views, we can impose constraints on the spatial analysis and discover new correlations.

Some approaches have proposed to consider spatial mobility in consecutive and recurring time intervals. In [43], the authors define an observation period of one week sliced in time intervals of one hour. By considering each recurring interval (from weeks to weeks for the same time interval) they analyzed the probability that the node in one destination will make the same transition to another destination. This analysis tries to characterize the correlation between transitions at particular times, for instance, the node will have a better probability to move from home to work between 8 and 9am than between 2 and 3am.

With the same time slicing, Boc *et al.* in [47] showed the correlation between the center of gravity of the observed mobility during a time interval and the center of gravity for the same time interval one week later. Their model is reactive to changes in behaviors and the analysis of more than 4900 mobile nodes on more than one year in a campus has shown high predictions success without even considering places of interest.

4.1.2 Discussion

The characterization of mobility is often context-specific. Despite the increasing number of publicly available data traces, they do not always provide the required spatial information to perform a detailed and complete analysis of mobility behaviors. When this is the case, the environment of analysis, the number of tracked nodes, and the durations of observation do not allow to obtain representative mobility characteristics. Although common characteristics rise from the analysis of several data traces, they come, most of the time, from the same type of context. On the top of this issue, it is difficult to perceive how the environment of analysis and the tracked devices can have an influence on the observed mobility. Michael *et al.* in [50] highlight the invasive aspect of nodes tracking with GPS. In their study, one user said that he tried to have more activities because of concerns about the quantity of data to be processed. Henderson showed that handled devices such as VoIP devices and PDAs have different mobility characteristics than laptops.

Concerning mobility patterns interpretation, there is a real problem in the accuracy evaluation of the clustering schemes. The works that propose such evaluation often use questionnaires and visual evaluations. Moreover, although natural, the durations of stay (or pause times) and the proximity are the only parameters used to define places. Because of the lack of analyses about what happens in such places, it is difficult to know if other parameters should be taken into account in places discovery algorithms or at least in the clustering evaluation.

With these issues in mind, we observe that, in almost all studies, there is a real concern about the filtering of the raw data traces. In wireless networks, the devices' behavior can introduce ping-pong effects (succession of associations/disassociations between two or more APs) at the association step. This behavior can mislead the characterization of mobility of the nodes. Despite the great number of proposals to determine places in mobility patterns for a wide range of tracking methods, deep mobility analysis does not consider the notion of places and only filter ping-pong effects. Hence, it is difficult to perceive if the observations made may have different weights if we make the distinction between nodes places and paths. For instance, we do not know what is the probability that a pair of nodes could encounter again in one place and in a path.

4.2 Routing/forwarding techniques

Traditional routing protocols assume that the communication end-points are always connected and that if a destination is not available, this implies that it is offline or a link in the route is down. No further effort is performed to guarantee a future delivery to the transmitted data. If the lack of connectivity is the normal state of a network and if the transmission paths are only available for short periods of time (if they will ever be available at all), the network protocols must be adapted for this new situation.

The concept behind *Opportunistic Networking* is that, in the absence of a fixed infrastructure which provides connectivity, the data could be transferred between network devices using the connection opportunities that arise from devices that come into wireless range of other wireless devices due to the node mobility. Intermittent connectivity is defined as the lack of any assurance that a connection will be available to any fixed or mobile access points at all times. In reality this means that it is not guaranteed that there exists an end-to-end path between the source and the destination at all times.

In opportunistic networks the data is forwarded when nodes are in wireless range, eventually carrying it closer to its final destination. In such an environment it is important to characterize how long are the transmission opportunities (*contact duration*) and how long are the time gaps between transmission opportunities (*inter-contact time*). In the absence of a transmission opportunity the data must be stored in queue in an intermediate node. If the inter-contact times are long this implies a long storage period, requiring a careful queue management, especially regarding how data is discarded when the queues are full.

Concerning the state of the art in routing protocols, there are two categorizations in literature. The first categorization is based on the type of network (*without infrastructure* and *with infrastructure*) [3] [51]. The second categorization is based on the evolution of the network [52].

According to the first categorization, we have:

- Algorithm that exploit some form of infrastructure:
  - Routing based on fixed infrastructure
  - Routing based on mobile infrastructure
- Algorithm designed for networks without infrastructure

If the future topology of the network is deterministic, the transmission can be scheduled ahead of time. Instead, if the time-evolving topology is stochastic, the best routing approach is to randomly forward the packet to the neighbors.

Moroever, there are certain protocols that use knowledge of the context where nodes operate to identify the best next hop.

- Routing protocols which belong to the Deterministic case are:
  - Tree approach
  - Space time routing
  - Modified shortest path approach

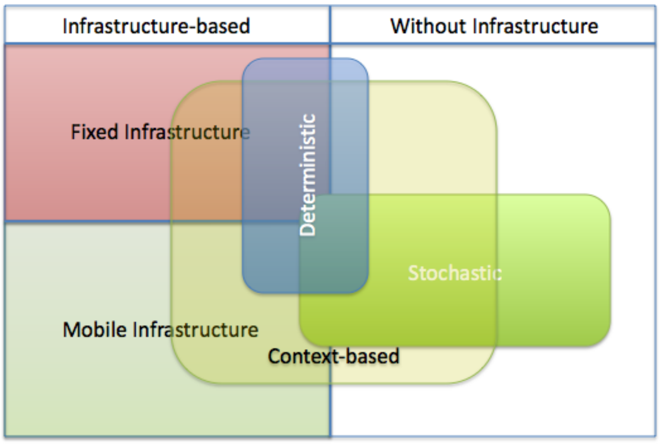

Figure 1: Categorization of routing protocols.

- Model based

- Those belonging to the Stochastic case are:
  - Epidemic/random spray
  - Coding based approach

- Context-based routing protocols are:
  - History or predication-based routing protocols
  - Control movement

The three categorizations overlap according to the Figure 1.

In particular, routing protocols which belong to the Deterministic case are more appropriate for networks based on fixed and mobile infrastructure, instead they are not convenient for networks without infrastructure; on the contrary, routing protocols belonging to the Stochastic case are more appropriate for networks without infrastructure. Regarding context-based routing protocols, in our opinion, they can be applied to both types of networks.

4.2.1 Algorithms that exploit some form of infrastructure

4.2.1.1 Routing based on fixed infrastructure

In Infrastructure-based networks, a source node usually wants to send a message through a base station which provides Internet access or acts as a router. There are two possibilities, the first is the Infostation model [53], which is an example of a direct communication between node and base station.

The other possibility allows the communication among neighbor nodes if the node is not in the range of the base station. The neighbor node will eventually forward the message to the base station. An example of the latter approach is the Shared Wireless Infostation Model (SWIM) [54].

4.2.1.2 Routing based on mobile infrastructure

In this type of networks, some (or all) nodes in the network act as mobile data collectors. These nodes move around in the network area following predetermined routes or random movements and gather messages from the neighbor nodes.

As an example, *Message Ferrying* (MF) [55, 56], is a proactive mobility-assisted approach which utilizes a set of special mobile nodes, called *message ferries*, to provide communication services for nodes in the network. Message ferries move around the deployment area according to a given, well known trajectory and take responsibility for carrying data between nodes.

In [57] a proactive scheme that modifies the trajectory of mobile nodes in ad hoc networks is proposed. This mechanism allows to guarantee that messages are delivered as fast as possible and network connectivity is maximized.

Obviously, mobility can be exploited to improve performance in sensor network scenarios as well. Here, networks are composed of tiny and battery powered devices. Reducing energy consumption is thus a major concern since it can allow an increase in network lifetime. Therefore, mobility should be exploited to decrease energy consumption. This is the rationale behind the DataMule concept [58]. Mobile entities (called *MULEs*) pick up data from sensors when in close range, store it, and drop it to wired access points. Therefore, DataMules achieve energy efficiency in sensor networks by using short-range transmissions. However, there are a couple of limitations: first, a sensor has to wait for a MULE to pass within range before it can transfer its data. Second, in some sense the MULE architecture simply transfers the burden of forwarding from sensors to MULEs, consequently, we expect MULEs to have much larger and more easily renewable energy resources than sensors. Moreover, the trajectory of the MULE may be either random or driven by the collected data, and thus, not known in advance by all nodes.

Developed by MIT Media Lab researchers, DakNet [59] has been successfully deployed in remote parts of both India and Cambodia at a cost two orders of magnitude less than that of traditional landline solutions. The DakNet wireless network takes advantage of the existing communications and transportation infrastructure to distribute digital connectivity to outlying villages lacking a digital communications infrastructure. Instead of trying to relay data over a long distance, which can be expensive and power-hungry, DakNet transmits data over short point-to-point links between kiosks and portable storage devices, called mobile access points (MAPs). Mounted on and powered by a bus, a motorcycle, or even a bicycle with a small generator, a MAP physically transports data among public kiosks and private communications devices (as an intranet) and between kiosks and a hub (for nonreal-time Internet access). Even a single vehicle passing by a village once per day is sufficient to provide daily information services.

4.2.2 Routing without infrastructure

In this kind of networks there is no knowledge of a possible path towards the destination; consequently a message should be sent everywhere. Routing protocols belonging to this class are essentially based on a random evolution of the network and will be discussed in sections 4.2.4 and 4.2.5.

4.2.3 Routing protocols belonging to the Deterministic case

In the networks based on infrastructures (even fixed or mobile) as those described before, it is highly probable the knowledge (or the predicability) of the hosts' trajectories. For this reason, in this class of networks it is more convenient to apply the routing protocols belonging to the Deterministic case, than in the networks without infrastructure.

As an example, in the tree approach [60], the routing algorithm selects the path of message delivery according to the available knowledge of the motion of hosts. This approach assumes a global knowledge of the nodes' motion with respect to space and time.

Most of the time the previous assumption is not true. For this reason space-time routing protocols [61] assume that the nodes' motion can be accurately predicted over a finite time interval. According to this knowledge, routing algorithms construct the best route using shortest path algorithms.

In [62], the authors introduce four knowledge categories called oracles; each oracle represents a certain knowledge of the network. The *Contacts Summary Oracle* provides information about aggregate statistics of the contacts (i.e. when there is an opportunity to transfer data). The *Contact Oracle* gives information about contacts between two nodes at any point in time. The *Queuing Oracle* provides information about instantaneous buffer occupancies at any node at any time. Finally, the *Traffic Demand Oracle*, contains information regarding the present or future traffic demand. Based on the available oracles, the routing algorithms act differently. The larger is the number of oracles available, the more accurate are the routing decisions.

In Model Based Routing (MBR) [63], the key idea is that mobile devices typically do not follow the random walk motion pattern but are carried by human beings. If MBR can rely on location information and user profile, it can choose the best relay towards the destination. Actually, how to obtain user profile is an open question.

Some studies concern vehicle communications, such as [64], where authors demonstrate that the motion of vehicles on a highway can contribute to successful message delivery. They assume that the messages can be stored temporarily at moving nodes while waiting for opportunities to be forwarded towards the destination.

A recent work is [65], where the authors propose SocialCast, a routing framework for publish-subscribe that exploits predictions based on metrics of social interaction (e.g., patterns of movements among communities) to identify the best information carriers.

In all the approaches seen before an end-to-end path (possibly time-dependent) is determined before messages are transmitted. In networks without infrastructure, it is very difficult to know the topology of the network ahead of time. In the following we present some protocols designed for this kind of networks.

4.2.4 Routing protocols belonging to the Stochastic case

In routing protocols belonging to the Stochastic cases, the delivery of messages is simply performed by diffusing them all over the network. Messages will reach the destination by passing node by node. High nodes' density and mobility can improve the contacts opportunity among nodes and consequently the delivery of the messages to the destination. On the other side, these approaches consume resources in terms of transmission resources and memory occupancy thus leading to high energy consumption.

In the Epidemic Routing category [66], the messages are diffused in the network similarly to diseases. A node is said *infected* when it generates or receives a message from another node. When two nodes are within communication range, the infected one sends the message to the neighbor node if it has not received the message yet (it is said *susceptible* to infection). An infected node becomes *recovered* once having delivered the message to the destination. Moreover, it becomes *immune* to the same disease, meaning that it does not relay the same message any more.

Another similar approach has been investigated in [67]. Here, a 2-hops forwarding approach has been considered. In particular, a node generating a message sends it to a randomly chosen node called *receiver*. When the receiver enters the communication range of the destination node, the receiver delivers the message to the destination. This approach, assuming that the message can be delivered only twice, limits the number of copies spread all over the network.

Recently, in [68], the authors consider (p, q)-Epidemic Routing, a class of store-carry-forward routing schemes, in which packets are forwarded blindly in a probabilistic manner. More specifically, a relay node (resp. source node) passes a packet copy to another relay node with probability p (resp. q) when they meet. (p, q)-Epidemic Routing includes the conventional Epidemic Routing, Two- Hop Forwarding, Probabilistic Forwarding as well as Direct Source-Destination Delivery [69]. Note that (p, q)-Epidemic Routing implicitly assumes that nodes have no knowledge about the network/node mobility and historic meeting information is useless for predicting future meetings. Such a situation typically arises when nodes move around independently and randomly.

The MV routing protocol [70] (meaning Meetings and Visits) is an improvement of epidemic routing. It introduces a method to select the messages to be requested from an encountered node. The choice depends on how much confident a node is to deliver these messages to their destinations. Hence, each node computes the delivery probability towards each other node in the network. The probability depends on observations on both the *meetings* between nodes and *visits* of nodes to geographical locations.

The *Spraying* protocol [71] limits the amount of broadcast messages forwarding them to a ray in the vicinity of the destination's last known location. It is assumed that the destination's last location is known and that there is a location manager in the system. The protocol relies on the fact that even though the destination may not be in the last location reported by the location manager, it is highly probable that it is in the surrounding locations.

The *Spray and Wait* protocol [72] outperforms the flooding-based routing schemes reducing the number of copies that can be transmitted per single message. Message delivery is divided in two temporal phases: the *spray* phase and the *wait* phase. During the spray phase, messages are spread over the network both by the source node and those nodes which have received the messages from the source node. This phase ends after a number of copies (which varies according to the adopted policy) are disseminated in the network. Then, in the wait phase each node holding a copy of the message simply stores its copy and eventually delivers it in case it comes into the communication range of the destination. The Spray and wait approach is extremely scalable, since, if the network density increases, the number of nodes which act as relays actually decreases.

Other protocols belong to the coding-based routing class. In particular, there are erasure-coding routing protocols [73] and network-coding routing protocols [74]. In erasure-coding routing, an original message is encoded into a large number of smaller code blocks. Usually, if the original message contains k blocks, using erasure coding, the message is encoded into n blocks ($n > k$) such that, if k of n are received, the original message can be successfully decoded. Protocols belonging to this class are pretty robust against packet losses due to bad channel condition, and can result very energy efficient (depending on the compression factor).

To improve the performance of erasure-coding approaches, in [75] a combination of erasure coding and estimation-based forwarding is proposed. In particular, after the messages are encoded, they are forwarded to different relays that have higher chance of delivering the messages.

Other approaches rely on network coding [74]. Using network coding, instead of simply forwarding packets received, intermediate nodes can perform a combination of packets belonging to different sources. Combined packets are disseminated all over the network and will be forwarded to the destination where the original packet can be reconstructed running the decoding process. The advantage of this approach is that the number of transmissions is reduced, and consequently the packet delivery ratio is much higher than the probabilistic forwarding both in dense mobile networks and sparse networks.

A stochastic analytical framework to study the performance of epidemic routing using network coding in opportunistic networks, as compared to the use of replication is presented in [76]. In particular, the authors show that network coding is improving the system performance when bandwidth and node buffers are limited, reflecting more realistic scenarios.

4.2.5 Context-based routing protocols

Protocols seen before simply forward packets to all or some neighbors. Unfortunately, this requires a huge amount of bandwidth and storage capacity and results very energy inefficient. In order to improve performance, some routing protocols exploit more information about the context in which node operates.

For example, in PROPHET (Probabilistic ROuting Protocol using History of Encounters and Transitivity) [77], each node, before relaying a message, estimates a probability called *delivery predictability* for each known destination. The calculation is based on the history of encounters between nodes or on the history of visits to certain locations. In particular, this metric has three factors: (i) it is updated whenever a node is encountered, so that nodes that are often encountered have a high delivery predictability; (ii) if a pair of nodes does not find each other for a while, they are less likely to be good forwarders of messages to each other, thus the delivery predictability values must age, being reduced in the process (according to a particular aging equation); (iii) delivery predictability also has a transitive property, that is based on the observation that if node A frequently finds node B, and node B frequently encounters node C, then node C probably is a good node to forward messages directed to node A. When two nodes meet, a message is sent by the node for which the delivery predictability of the destination of the message is higher. The first node does not delete the message after sending it as long as there is sufficient buffer space available (since it might encounter a better node, or even the final destination of the message in the future). Simulation results show that PROPHET outperforms epidemic routing in terms of both delivery success rate and delay.

In MobySpace Routing [78], the forwarding algorithm is based on a high dimensional Euclidean space where each axis represents a possible contact between a couple of nodes, and the distance along an axis measures the probability of that contact to occur. Two nodes are said *close* when they have similar sets of contacts and they experience those contacts with similar frequencies. It is worth remarking that this approach requires the knowledge of the number of nodes in the considered space.

The Context-Aware Routing protocol (CAR) [79] uses two approaches for message delivery. For each node, when a packet arrives, if a a path to destination exists, the packet is forwarded to the corresponding next-hop. Otherwise, if a path to the destination cannot be found, instead of replicating the message to all the neighbors, the node selects the best next-hop. The attributes for the election of the best next-hop are, for example, the residual battery level, the buffer capacity, the degree of mobility, etc. CAR has been tested through simulations and results show that the delivery ratio of CAR is better than Epidemic routing.

4.3 Novel scheduling, resource allocation and MAC schemes

The aim of this Section is the discussion of scheduling and radio resource assignment in opportunistic networks. DR8.1, a deliverable of WPR8 dealing with scheduling and radio resource assignment, is released in parallel to this document, and reports a thorough SoA on the topic. Therefore only issues connected to opportunistic networks are discussed here, while more general aspects of scheduling have to be found in DR8.1.

4.3.1 Some Definitions

Scheduling and Resource Allocation are terms used with different meanings in the literature. It is therefore worth introducing some general definitions that will be useful in the next sections to avoid misunderstanding. However, what follows is not meant to be taken as universally agreed; rather, it should be regarded as one possible way to present some concepts which, of course, finds wide correspondence in the literature although not being the only one.

We refer to *Radio Resource* (RR) to indicate the signal format used by a given flow to transmit data. A *Radio Resource Unit* (RU) is the minimum amount of RR that can be assigned (i.e., the one allowing the minimum amount of data to be transmitted). The RR is therefore defined in terms of energy, modulation format, codes, etc. . . .

The *Radio Resource Management* (RRM) entity aims at maximizing the system efficiency by ensuring a high level of resource sharing among users, avoiding wastes, meeting priorities and guaranteeing QoS. The RRM may be either centralized or distributed. In the first case the algorithms are run by a central controller which processes data from every node: if the network is large the cost is very high due to signaling overhead. In the second case the algorithms are run on every node at lower cost but also lower performance.

According to the following definitions:

- *transmit time interval*: the maximum duration of the signal format employed;
- *scheduling interval*: the time interval between two successive scheduling decisions (usually a multiple of the transmit time interval);

the *scheduler* is referred to the RRM functionality which assigns RRs in a given scheduling interval to all or a subset of the flows, such that a transport block of certain size can be generated at the beginning of each new transmit time interval for each of the flows. In general, any kind of network resource (e.g. energy, etc. . .) may be scheduled.

The *resource allocator* maintains a record of the (still) available resource budget and non-scheduled users/flows. When asked to determine new proposals, it first checks whether a new scheduling process has started. If this is the case (i.e. there exists no previous "best" proposal in the scheduler), the resource allocator resets all records to their initial values. Otherwise, all resources required for the last "best" proposal are removed from the resource budget and the respective users/flows are marked as already-scheduled. If the available resource budget is non-empty and there exist still-unscheduled users/flows, valid proposals are then assembled and forwarded to the scheduler. During the assembly process, the state of the system is typically considered depending on the level of "intelligence" of the resource allocator.

A new scheduling process starts by requesting proposals from the resource allocator for the initial resource budget available in the system. Each of these proposals may either consume up to the whole available resource budget or contain one of the following user/flow combinations:

- one single non-scheduled user/flow: there is no joint allocation (it requires low "intelligence" in the resource allocator);
- multiple flows from a single user (if transport block multiplexing is allowed at the air interface): intra-user joint allocation is needed (it requires medium "intelligence" in the resource allocator);
- multiple user/flow combinations: inter-user full joint allocation is needed (it requires high "intelligence" in the resource allocator).

The scheduler then decides for one of the proposals offered by the resource allocator based on the respective scheduling metric in use (the latter should be computable from the state of the system and the information contained in each proposal). This "best proposal" is then added to the new schedule. Since even the best proposal does not usually consume the whole available resource budget (which is especially true in case of a "low-intelligence" resource allocator), the scheduler might decide to run another round for the remaining users/flows. In this case, scheduling ends as soon as the resource allocator no longer produces valid proposals.

It is worth noting that scheduling requires knowledge of the resources to be scheduled: typically, when RRs are to be assigned in heterogeneous environments (i.e., a variety of different devices are present), the resource allocator must be aware of the air interface that a given user possesses in order to assign a suitable RR. On the other hand, diverse RRs may be modeled as abstract entities and hence be treated by the scheduler independently of the air interface.

Recently, the potential advantages of using cross-layer techniques in scheduling over shared channels have been investigated [80]. Unfortunately, in multi-user environments scheduling operations become more and more complex as the number of users competing for the wireless shared channel increases. For this reason, a fully optimized scheduling is most of the times unaffordable. More often it is necessary to resort to sub-optimal solutions.

4.3.2 Impact of Opportunism in Scheduling, Resource Allocation and MAC

In this section we revise some approaches related to the two main categorization of opportunism seen in Section 2.

The first kind of opportunistic network we have referred to as "oppnets" in Section 2 requires suitable radio resource management schemes, since it is composed of nodes accessing the radio channel via different air interfaces. To achieve the optimal distribution of resources among multiple users, the scheduling and resource allocation units should, in general, be unified and consider all users jointly in the optimization process. In this case, however, since a fully optimized scheduling could require an infeasible complexity, it may be useful to split it in some steps, even though it leads to a suboptimal solution. This approach was introduced in some recent works (e.g., [81, 82, 83]) from which a general framework that takes into consideration realistic channel and traffic models as well as a cross layer interaction between physical, data link and higher layers may be developed. Therefore, it is convenient to define a formal separation of the whole scheduling function into two sub-functionalities, namely, resource allocator and scheduler. The main reason of this, is the heterogeneity of radio devices present in the network and, as a consequence, the heterogeneity of RRs employed. In fact, two nodes may, say, transmit and receive at two different frequencies and/or use different coding techniques. Thus, scheduling decisions must take into account what kind of RR is to be assigned to a given node, based on its physical layer. Therefore we assume the resource allocator to be fully air interface aware, so that it can define an abstract concept of RU and provide the scheduler (that we assume air interface unaware) with it. Then, the scheduler can take its decisions based on the application needs, by working on a pool of abstract RUs that it can treat as they were homogeneous. This structure is formalized in such a way to be applicable to any wireless system, especially when different air interfaces are involved (e.g., in the heterogeneous environment typical of opportunistic networks). This conceptual differentiation affects the operations performed by each unit: in fact, in order to decide which users are allowed to transmit and on which radio resources, we assume that an iterative process between resource allocator and scheduler takes place as described in the following. At each round of the iterative process the resource allocator formulates a set of allocation proposals. The set contains one proposal for each user with non-empty radio link buffer, based on the currently available common resource budget and considering that at most $N_{RUmax,u}$ RUs per user can be allocated at each round. The different proposals may share part (and, at most, the whole set) of the RUs available. The resulting set of proposals are forwarded to the scheduler, which selects only one of them, denoted as "best proposal", according to the implemented scheduling policy. After this decision, the resource allocator removes the resources required by the selected best proposal from the budget, and determines a completely new round of proposals based on the remaining resource budget, which are again forwarded to the scheduler and so forth. This iterative process is repeated until either all users have the buffers emptied or the resource budget has been consumed.

The second kind of opportunistic network we have referred to as DTN in Section 2 does not present relevant MAC and scheduling issues. In fact, due to sparsity, network communications reduce to communications between pairs, thus not needing resource allocation among a multiplicity of users.

An exception is the case of Sensor/Actuator Networks where each sensor alternates between active and sleep states to conserve energy with an average sleep period (much) longer than the active period. In fact, alternating sensors between on and off (active and sleep) states unavoidably disrupts the network operation, e.g., coverage and connectivity [84]. In order to compensate for potential performance degradation due to such disruption, redundancy in sensor deployment is usually added. Intuitively, the more redundancy there is, the more we can reduce the duty cycle for a fixed performance measure. For a given level of redundancy, how much the duty cycle can be reduced depends on the design of the duty cycling of the sensors, i.e., when to turn the sensors off and for how long.

All the sleep/active cycle schemes are implemented as part of the MAC layer protocol [85]. The two main characteristics of such schemes are the duty cycle and the synchronization. Protocols such as S-MAC, T-MAC and D-MAC [86, 87] have been designed based on different configuration of these parameters.

Two significative scheduling trends in the recent literature [85, 88] are the *random sleep* schedules, whereby each sensor enters the sleep state (turned off) randomly and independent of each other, and *coordinated sleep* schedules, whereby sensors coordinate with each other to decide when to enter the sleep state and for how long. An obvious advantage of the random sleep approach is its simplicity, as no control overhead is incurred. On the other hand, using coordinated sleep leads to a better controlled effective topology and is thus more robust and can adapt to the actual deployment. The price to pay is the overhead and energy consumed in achieving such coordination. Moreover, coordinated sleep schemes are much harder to analyze and optimize.

5 JOINT RESEARCH ACTIVITIES PROPOSALS

During the WPR11 kick-off meeting held in Catania on March 13-14 2008, several JRAs have been identified in accordance with the background research competencies and interests of each partner.

In this Section, we only discuss the JRAs which have been started already, with the indication of the partners who declared involvement for each JRA (the partner in bold represents the JRA's leader, i.e. the partner who will behave as catalyst), namely:

- Opportunistic localization and tracking. Partners: **CNIT-PD**, *CNRS/LAAS, RWTH, ISMB*.
- Mathematical modeling of intermittent behavior in opportunistic networks. Partners: **NKUA/IASA**, *CNIT-CT*.
- Routing in opportunistic networks. Partners: **CNIT-CT**, *CNRS/LIP6*.
- Peer-to-peer techniques in opportunistic networks. Partners: **Bilkent/KHAS**, *ISMB, CNIT-CT, CHAL/KAU*.
- Opportunistic connectivity: the impact of nodes mobility. Partners: **CNIT-BO**, *RWTH*.
- Experimental activities. Partners: **ISMB** - *CNIT-TO* - *CHAL/KAU*.

In addition, two additional activities have been envisaged, being related to cooperation with other WPs:

- Coding in opportunistic networks. Partners: *CNIT-CT (WPR11)* and *TUM (WPR5)*.
- Opportunistic spectrum access. Partners: *UPC (WPR11)* and *CNRS-Supelec, CNIT-BO, CNRS-Eurecom (WPR9)*.

It is worth mentioning that some other research activities have been identified and proposed but they have not been activated yet as JRAs, and therefore their description will be reported in the next deliverable. They are the following:

- Transport Layer issues in opportunistic networks.
- Fundamental throughput limit in opportunistic networks.
- Horizontal activity on the Resource Description Language Framework.

In the following, each subsection covers a specific JRA started already, with the indication of the partners involved, the objectives of the JRA, and how the activity will be carried out.

5.1 Opportunistic localization and tracking

PARTICIPANTS: **CNIT-PD**, *CNRS/LAAS, RWTH, ISMB*

5.1.1 JRA definition

The aim of the JRA is to devise, design and analyze novel opportunistic schemes aimed at enhancing the self-localization and tracking functionalities of some mobile nodes in a given area.

We envision an indoor scenario where nodes have different mobility patterns, including static (Access Points, Beacons, static Motes), periodic and/or pre-planned (elevators, mobile stairs, stairlifts, robots), preferential (errand girls, office workers, maintenance men), and random. Furthermore, nodes might be equipped with a different number of wireless communication interfaces, such as Bluetooth, WiFi, 3G, Mote, and so on. We also assume that some nodes might be equipped with sophisticated localization modules (as cricket, MEMS, indoor GPS), whereas others might be able to perform only a simple (and rather unreliable) RSSI–based localization. All these nodes are assumed to be able to seamlessly and opportunistically interact to obtain certain objectives and, in particular, to improve their own localization estimate.

The JRA will investigate how the localization error of a node can be reduced by opportunistically exchanging information with other nodes.

The JRA is essentially divided in two parts: the first one has the objective of understanding and modeling the mobility of the nodes in a realistic indoor scenario and the opportunistic interaction between two nodes; the second one is focused on the localization problem and aims at modeling the localization enhancements that can be obtained by exploiting the opportunistic data exchange.

5.1.2 Research challenges

Opportunistic localization and tracking opens the way to several research challenges, some of which are listed below.

1. **Node discovery and link establishment.** In opportunistic networks a very important task is to exploit every possibility to communicate with other nodes, in order to gain information and, in our specific case, improve the localization. However, nodes can have single or multiple communication interfaces, with different transmission rate and coverage, as well as different energy constraints, mobility patterns and so on. Therefore, the realization of efficient nodes discovery and link establishment algorithms is a very interesting and important research challenge.

2. **Mobility model.** The most common mobility model used in simulations and/or analytical studies is the random way point. However, this model hardly reflect actual mobility patterns, in particular when considering human activities or automated environments. Since the mobility model can potentially have a strong effect on the performance of an opportunistic localization system, the definition of a realistic and flexible mobility model and the investigation of the impact of such a model on the performance of the system is of fundamental importance.

3. **Self-localization error model**. Similarly to what observed concerning the mobility model, also the modeling of the localization error can strongly affect the system design and performance. Therefore, it is essential to provide a statistical characterization of the error distribution with different localization techniques. To this end, collaboration with Work Package WPR.B is desirable.

4. **Opportunistic localization improvement.** Assuming that data can be opportunistically exchanged among nodes, the problem of how using such an information to improve the node localization remains to be solved.

5. **Experimentation**. In order to evaluate the effectiveness of the proposed solutions, both simulation and real world experiments have to be performed. This requires the development of new simulation

modules and the accurate definition of several marginal aspects, which are necessary to realize the system in practice.

5.1.3 *Work Plan*

Due to the size of the problem, we adopt a *divide-et-impera* approach splitting the activities into two tasks, each addressing a subset of the challenges described in Section 5.1.2. In a following phase, the knowledge gained from these two research activities can be merged to devise an integrated solution for the whole problem.

In the following, we describe the two JRA tasks:

5.1.3.1 Task 1: Mobility model and opportunistic data exchange

`Research Team: CNIT-PD - RWTH - CNRS/LAAS`

This task will address the aspects related to the opportunistic exchange of data, which consists in node discovery and link establishment under a suitable mobility model. The error model and localization enhancement, on the contrary, will be modeled in a rather simplified manner. For instance, localization errors can be assumed to have Gaussian distribution, with variance belonging to a limited number of classes. When two nodes opportunistically exchange data, the variance of their localization error can be updated according with some simple scheme (weighted average or similar). The focus of the task, instead, is on the following aspects:

- Mobility model (CNRS/LAAS):
  - How to model the node's mobility?
  - How long will two nodes remain in-range?
  - What's the probability of meeting another node? of which "class"?
  - Is it possible to identify a limited number of significant mobility patterns?
  - How can nodes learn about their mobility pattern?
  - Does it make sense to broadcast info concerning your own mobility pattern?
- Opportunistic data exchange (CNIT-PD - RWTH):
  - Identify the available wireless interfaces
  - How long does it take to establish a link?
  - How long does it take to exchange data?
  - How many often shall HELLO/BEACON messages be broadcasted?
  - Issues about transmission power
  - Dynamic transmission-adaptation techniques for improving reliability

5.1.3.2 Task 2: Localization error modeling and opportunistic enhancement

`Research Team: CNIT-PD - ISMB - RWTH`

The second task, which is (to some extent) complementary to the first one, mainly addresses the aspects concerning the modeling of the self-localization error and the techniques to gain advantage from the info received from other nodes. The mobility and the link establishment aspects, therefore, might be superseded considering some simple (though acceptable) models (single interface with given coverage range, simple distribution of the in–range time). Then, the activity shall focus on the following points:

- Error modeling (ISMB).

  - How can we model the different non-cooperative localization performance (depending on the interfaces, the number and the distance of beacon nodes, what-else)?

- Localization improvement (ISMB - RWTH - CNIT-PD).
  - How can we merge the localization info received by different nodes?
  - How should we weigth the localization info received from another node?
  - Do we need to make some hypothesis on the scenario or is it possible to abstract it in a general way?
  - How can we exploit info related to other nodes that have been met along the way?

5.2 Mathematical modeling of intermittent behavior in opportunistic networks

PARTICIPANTS: **NKUA/IASA**, *CNIT-CT*

5.2.1 JRA definition

The main objective of this research activity is to study the aspects of intermittent dynamics in opportunistic networks.

Let us consider a scenario where mobile nodes move and exchange some data packets throughout the network. A certain node S, wants to send some information to node D_1, some other info to node D_2, etc. These nodes, while moving throughout the network, can opportunistically exploit other nodes in their proximity, in order to relay their data packets and, thus, finally delivering this data to the intended destinations. This mechanism implies neighbor nodes cooperation and interaction in the view of allowing responsive delivery to the destinations. Opportunism in this perspective relies on the fact that, some data tolerant applications, can exploit nodes mobility so that, even if the source node is not in the coverage of the destination node, data can be forwarded without implying any modification to nodesŠ trajectory. This implies a sort of flooding throughout the network.

It is well known [91] that under certain conditions networks tend to reach self-organized critical states, due to the presence of large avalanches that tend to make all sites interact with each other. Usually this problem is treated in the case of static networks, which is a realistic assumption for internet traffic through fixed nodes and connections. It is not clear how these concepts will apply in the context of wireless networks, where the network itself is evolving in a time-dependent fashion, due to signal interference and fading of the channel. Therefore, in the context of opportunistic networks, where in addition to fading and interference, users are assumed to move around and exchange information opportunistically, it would be interesting to analyze the effects of avalanches and examine whether the system reaches a self-organized critical state.

5.2.2 Open issues/goals

We intend to analyze this problem using statistical mechanics tools, such as mean-field theories and renormalization-group arguments, as well as other tools and numerical simulations. We plan to pursue the following general directions:

1. Analysis of queue-triggered opportunistic networks: In this case we will study a different type of opportunistic networks, where the nodes are turned on to transmit only if their queue length is greater than a given length

2. Analysis of effects of temporal variations of node-strength (fading).

3. Analysis of effects of interference.

4. Analysis of effects of user mobility.

5. When a node relays opportunistically its data packets to a neighbor node met occasionally, does the original sender node need to keep a copy of the packet and relay it also to other nodes? We think this is expected and can be useful to increase the chance to have a successful delivery of data at the final destinations. But how many copies should be relayed?

6. Should all the packets relayed to close neighbors have the same weight in terms of causing the avalanche effect or should we weight differently the weight of a packet based on the distance between the source and the final destination?

7. How can we avoid incurring in an avalanche broadcast storm problem?

8. It would be nice if we could design an algorithm specifically thought to allow proper data forwarding through exploitation of the avalanche effect. This algorithm should be optimized to give some guarantees in terms of delivery probability.

5.3 Routing in opportunistic networks

PARTICIPANTS: **CNIT-CT**, *CNRS/LIP6*

5.3.1 JRA definition

The aim of this JRA is to design and analyze novel schemes and algorithms to improve routing efficiency (throughput, energy consumption, etc.) in opportunistic networks.

Traditional MANET and Internet routing/forwarding techniques have not been specifically designed for opportunistic networks and are not suitable for a number of reasons. First of all because they implicitly assume that the network, even if sparse, is connected (or can be made, e.g. by tuning transmitting powers) and an end-to-end path always exists between any source and destination. Moreover, classical techniques typically follow statically computed algorithms, which may consider the current properties of perspective relay nodes, but NOT the dynamic evolution of parameters characterizing potential contact opportunities among nodes.

Geographical routing protocols [93, 95, 97] on the contrary are scalable and they do not need an explicit route establishment. These algorithms refer to nodes by their location and use those coordinates to route greedily, when possible, towards the destination. Due to the high dynamic behavior of opportunistic networks, geographical routing techniques represent one of the most suitable routing techniques for this kind of networks.

Furthermore, a relevant aspect that should be taken into account when dealing with opportunistic networks is nodes' mobility. It represents an opportunity for communication because it increases the probability that a message can be delivered to the destination, even if on the other side it decreases the time needed for the data exchange.

For these reasons, it becomes of high importance to identify realistic mobility models in order to improve the protocols' design and to provide performance results close to the reality [92], [96].

From the expertise of the CNIT-CT, we focused more (but not limited to) the context described in the paper [93]. In this paper, the authors consider an environment without infrastructure where mobile nodes are/can be equipped with a global positioning system. In such a mobile context, CNRS/LIP6 argues that beyond the aspect of using positioning systems, routing efficiency undergoes the lack of information on where, when, and in which direction contributing nodes (in the forwarding sense) are likely to move. CNRS/LIP6, with its experience on users mobility behavior analysis [98], proposes to investigate how nodes themselves could obtain such mobility information by sensing their environment and provide this knowledge to the routing layer in order to take appropriated decisions. If it is possible to know that one particular node at time t_0 could contribute to the forwarding but at the instant t_1 will move in a completely different direction then, maybe it will be more useful to forward packet to another contributing node that will remain static or will move in the right direction. This means that node movements would become "links" in the geographic space.

Moreover, it is possible to exploit mobility considering network coding inside MACRO or MACRO+ [94]. Specifically, if node B will meet simultaneously nodes C and D at t_2, then it might be interesting for some node A to let node B carry data packets for both C and D. To be exploitable, such an approach should respect some constraints:

- Mobility characteristics of the nodes should be as close as possible of the ones observed in real environments.
- The time scale of the evaluation process should be long enough to analyze and characterize mobility.

In such situation, each (mobile) node should be able to provide to the other nodes with mobility information that could infer:

- How long it will stay at a particular location.

- In which direction it will move afterwards.
- Which nodes it will likely meet in short, medium, and long term.

A possible goal of the JRA is to investigate the cost of providing this kind of information, to use this information, and to evaluate the possible resulting routing improvements.

5.3.2 Open Questions

In order to reach the above describe goal, we need to provide answers to a number of open questions.

1. **Assumptions**. What type of the nodes (mobile users, sensors, cabs, etc.) should we consider? What are the capabilities of the nodes? Do we consider that all nodes have global positioning capabilities? Could we infer, in a first time, the position of the nodes according to a fixed infrastructure? What kind of reference scenario should we address first? Could we use resulting mobility information from the mesh network of Bilkent/KHAS? Do we have to define generic mobility models inferred from real data traces?
2. **The evaluation time scale**. Learning mobility patterns takes time. The resulting improvements would then be delayed in the time. We clearly face a tradeoff problem: on the one hand, if we consider a too short time scales, improvements might be negligible; on the other hand, choosing too long time scales would introduce complexity in how to handle mobility history.
3. **Useful information for routing**. What are the information that should be considered as important for routing and beyond (network coding)? Is it useful to know which nodes will be encountered in the long term? Do we have to consider data lifetime?
4. **Practical representation of the information**. The amount of information that could be provided by neigh- boring nodes can increase the complexity in the routing decision plane. Is there a way to encode/present the information to reduce such a complexity?

The research conducted in this JRA could be organized into the two following activities:

5.3.3 Activities

- Identification of new relevant application scenarios and mobility characterization;
- Evaluation of MACRO improvements when the mobility information is used.

5.3.3.1 Identification of new relevant application scenarios and mobility characterization

This activity can be split into two phases. The first phase is related to identify a set of relevant application scenarios where it is possible to apply MACRO as routing protocol. The second phase is related to the characterization of the users' mobility in the application scenarios already identified.

5.3.3.2 Evaluation of MACRO improvements when the mobility information is used

The goal of this activity is to evaluate the performance of MACRO protocol when the mobility information is exploited.

5.4 Peer-to-peer techniques in opportunistic networks

PARTICIPANTS: **Bilkent/KHAS**, *ISMB, CNIT-CT, CHAL/KAU*

5.4.1 Introduction

Due to their distributed nature, P2P networks can and have been used for a wide variety of applications. Two general classes of P2P networks can be identified. First-generation P2P networks have been largely used for popular file-sharing applications (e.g. Kazaa [99], and Gnutella [104]). These systems are also referred to as unstructured P2P networks since they usually do not impose any structure on their topology. Instead, nodes connect to each other largely at random. The network uses flooding as the mechanism to send queries across the overlay with a limited scope. When a peer receives the flooded query, it sends a list of all content matching the query to the originating peer. Flooding-based techniques are effective for locating highly replicated items and are resilient to peers joining and leaving the system, but are poorly suited for locating rare items, and are not scalable as the load on each peer grows linearly with the total number of queries and the system size.

To overcome the scalability issues of the unstructured approach, structured P2P networks have been proposed, where the P2P overlay network topology is tightly controlled. Content is placed not at random peers but rather at specified locations that will make subsequent queries more efficient. Very popular representatives of structured P2P networks are realized through the so called Distributed Hash Tables (DHTs) (e.g. CAN [100], Chord [103], Pastry [102], and Bamboo [101]), in which data object (or value) location information is placed deterministically, using unique keys of the data objects corresponding to the peers identifiers. DHT-based systems have the property that uniform random NodeIDs are assigned to the set of peers in a identifier space. Data objects are then assigned to unique identifiers called keys, chosen from the same identifier space. Keys are mapped by the overlay management protocol to an unique live peer in the overlay network. As a result, P2P overlay networks support scalable storage and retrieval of key,value pairs on the overlay network but might suffer from control traffic overhead necessary for ensuring consistent structure.

The intent with this JRA is to investigate how different P2P techniques can be used in Opportunic Networks and to investigate the design and issues of P2P systems/application over opportunistic networks.

5.4.2 Activities

Since the partners participating in this JRA have no prior experience working together in the area of the JRA, the activities in the first stage of the project are focused on identifying the most beneficial areas for resaerch collaboration within the general area of P2P systems in opportunistic networks. Some initial ideas for collaboration along with the process for defining a detailed JRA is briefly outlined below.

5.4.2.1 Initial Ideas

P2P networks and opportunistic networks have many things in common, but there are differences as well. P2P networks are characterized by decentralized nature; anonymity; P2P interactions; dynamic topology, etc. Opportunistic networks are characterized by intermittent connectivity; heterogeneity, connectivity opportunities through mobility, multiple interfaces, multiple access technologies; centralized or decentralized service access; dynamic topology, etc. In this JRA we will focus on the identification of similarities and differences between P2P networks and opportunistic networks, and on the issue of how their problems, design, analysis, and implementation can benefit from and interact with each other.

The following are the general issues that need to be investigated:

- How can we apply P2P techniques that are developed so far for the problems of opportunistic networks. There is a good amount of literature on P2P resource discovery, query routing, neighbor discovery, connection establishment and P2P interactions. Similar problems need to be solved in opportunistic networks as well. For example, neighbor discovery and opportunistic resource discovery are some of the problems of opportunistic networks that can benefit from solutions developed for P2P networks. Similarly, caching, replication solutions for P2P networks can be adapted for opportunistic networks.

- The traditional P2P applications/services that are developed so far may be considered to be run over opportunistic networks as well. The connectivity characteristic of opportunistic networks, however, are very different than the connectivity characteristic of P2P networks. Usually P2P networks assume that a peer will find another peer to connect to in a short amount of time. If a peer loses its connection to a peer, it can easily find another peer through which it can connect to the network. But this is not always the case in opportunistic networks. A node may be disconnected from the network for extended amount of time and during this time it may not find any other node to which it can connect. For this environment, caching of data becomes more important issue. Similarly, queries can not be resolved immediately. Queries may have to be buffered in intermediate nodes for a long time. Additionally, use of TCP for connections between nodes may not be a good idea in opportunistic networks. Therefore there is a need to investigate how we can adapt the existing P2P applications to run over opportunistic networks.

- P2P applications/services in hybrid networking scenarios, involving islands of connected nodes with opportunistic connectivity to the outside world, is another interesting topic. In next-generation networking environments, wireless mesh and multihop networks are expected to become more widespread as internet access network technology. Such challenged networks may not always have internet connectivity. Instead, such mesh islands may be connected in rather opportunistic ways in rural areas. Caching and query handling, as discuseed above, will be important here as well. In such environment it is also crucial to make the network self-organizing and self-managing to reduce operational costs and make it easy and fast to deploy. These are areas where P2P techniques have much to offer.

5.4.2.2 Refining the JRA

Some highly preliminary ideas for collaboration were desribed above. The initial ideas will be complemented and refined according to the following process:

1. As a first stage an extended information exchange will take place between the partners. The most relevant previous resaerch results, obtained by each partner, will be circulated. This stage will be conducted during April and May.

2. The second stage will consist of a brain-storming period. Based on the gained knowledge of each partners competence and interests differnt possibilities for joint research activities will be discussed and evaluated. This stage will be conducted in June.

3. In the third stage detailed definitions of JRA activities will be established. Due to the different vacation periods in Europe, this stage will extend from July through September.

4. Having established a detailed JRA, implementation of the joint research activities will then start in the fall.

5.5 Opportunistic connectivity: the impact of nodes mobility

PARTICIPANTS: **CNIT-BO** - *RWTH*

5.5.1 JRA definition

The aim of the JRA is to introduce and analyze novel scenarios for wireless ad-hoc and sensor networks. The emphasis will be put into considering more classical connectivity and MAC issues while jointly accounting for the opportunistic behavior of the network.

This activity is intended as an extension of a JRA proposed by the same partners within WPR10, which addresses connectivity and MAC aspects. In particular, a typical scenario that we consider consists of two types of nodes (sensors and sinks) randomly deployed on a finite area at given densities. Sensors are supposed to collect data samples from the environment and transmit them to the sinks, which are in charge of aggregating the information. This requires a high level of connectivity of the network and hence performance metrics such as the non-isolation probability are of great interest in this context. In WPR10 we aim at exploring the impact on connectivity of more sophisticated spatial distributions of nodes than the usual Poisson Point Process, which does not accurately describe clustered networks.

The MAC layer is also considered by means of the derivation of the probability of success. The particular case of CSMA-like protocols (such as the IEEE802.15.4 MAC protocol) is treated.

Given the JRA that we set up for WPR10, which has been briefly summarized, we address an extension of this work to be carried out within WPR11. In particular, we believe that a greater depth into the opportunistic concept could be gained by considering the intermittent behavior of opportunistic networks, along with the issues already addressed in WPR10. In fact, this element might reveal as being very insightful and have great impact on connectivity and MAC. For instance, the temporary unavailability of connections among nodes due to mobility, intermittence, etc..., would produce significant changes in the network topology. To this end, we need to include suitable mobility models in our framework, based on both off-the-shelf mathematical tools and more realistic measured patterns.

To be more specific, there are three possible situations involving mobility, all being interesting with respect to different applications:

1. stationary sensors and mobile sinks;
2. mobile sinks and stationary sensors;
3. mobile sinks and mobile sensors.

The analysis of such scenarios will also bring substantial insight on practical design issues regarding MAC protocols, routing and forwarding algorithms. The tools we intend to adopt are both mathematical modeling and simulation.

5.6 Experimental activities

PARTICIPANTS: **ISMB** - *CNIT-TO - CHAL/KAU*

5.6.1 JRA definition

The paradigm of opportunistic networking brings intrinsically ideas of experimental activities: the definition itself of the paradigm is something which is achieved from experience rather than theoretically defined *a priori* (and then applied to a context).

Additionally the opportunistic networks are based on a mobility concept which is very “various” and spans from vehicular to pedestrian mobility, from highway to urban - and even indoor - environments and involves different wireless standards (which supports different mobility tools): this kind of “freedom” can be hardly univocally modelled and involves a practical experience.

As a result most of the Joint Research Activities which can be proposed in the field of opportunistic networks include a practical side or an underlying experimental concept: for instance the mathematical modelling of intermittent behaviour (as well as of the mobility) requires a real trace of mobile nodes, in order to be effective; the routing analysis cannot be based on fixed scenarios or on simplistic connectivity models, because this would invalidate the analysis: so it must rely on a realistic mobility model; the same is for the evaluation of available bandwidth and for the estimate of the available bandwidth for the opportunistic network.

So the rationale of a set of joint research experimental activities is to:

- Select some common development platforms whose features (HW configuration, SW code, results) can be shared among partners as an experimental benchmark.
- Support the activity of mobility modelling (and intermittent connectivity) by experimental tracking of nodes, also by a synergic cooperation with the JRA of localization.
- Provide practical hints on the real behaviour of networks (based on experiments) to feed the other JRAs (even if to the limited extent of a limited number of nodes and functions).
- Validate the models and protocols developed by the other working groups of WPR.11.
- Achieve a certain awareness on the practical and short-term feasibility of the networking and or application solutions identified by the other working group.

For this reason the next two sections are meant to provide respectively a short overivew on the available platforms which can be used for the experimental activities 5.6.2 and a set of short- and medium-term practical objectives.

5.6.2 Available Platforms

Today there is a wide range of different platforms which can serve as base building blocks for experimental activities in the field of wireless networking. However, considering the goals which have been stated in 5.6.1, the platforms should be preferably restricted to the ones which are: based on an open operating system, able to support multiple and different kind of wireless interfaces, easily procured, not too expensive (in order to allow a certain scalable “cardinality”), adaptable to a certain set of experiments and applications.

Moreover, considering the conceptual studies which are planned within WPR.11, the radio standards involved in the experimental activities could be a large set (namely WiFi, WiMax, UMTS, ZigBee, ...), nevertheless, considering the goals of the proposed activities, as a first approximation, the use of only two main interfaces (and consequently, platforms) is suggested: Zigbee (or ZigBee-like) interfaces, to achieve a hands-on awareness in the field of short-range and power-constrained transmissions (they are commonly accepted as the WSN reference interface); WiFi for all the other cases.

The idea of splitting the problem into two issues is meant to guarantee two parallel research paths respectively for low power and broadband wireless connections, which are too far the one from the other; on the other hand one could take exception that collapsing all the other wireless technologies into the only WiFi would be too restrictive to the general approach of opportunism. However, considering the high-level research contents of opportunism, it can at some extent rely on an abstraction of the physical and MAC layer (when an appropriate QoS can be provided) and, notably, WiFi offers several experimental benefits which certainly overcome the number of limitations: WiFi is cheap and unlicensed, offers also open source drivers, has a scalable number of non overlapping channels (which can emulate different wireless stds), can work both in ad hoc and infrastructure and at different speeds (both configurable or dynamically set) and this too can serve the emulation of other wireless standard in the work frame of opportunism, also for some early tests in the field of vehicular networks, currently addressed by the IEEE 802.11p std (not available yet but based on several concept of the precursor std IEEE 802.11a/b/g).

5.6.2.1 WSN Platforms

Concerning the realization of test-beds and the subsequent testing activities on WSN technology, as a particular type of opportunistic network, Crossbow platforms in particular are commonly accepted and adopted in the scientific community [105].

These embedded devices can be programmed through the free TinyOS operatingra system and NesC programming language. A number of components and interfaces are available under open-source distribution.

In particular, Telos revB and Imote2 platforms are the most recent, powerful and reliable platforms. They both adopt the TI CC2420 radio transceiver, implementing the IEEE 802.15.4 protocol stack for the lowest layers. The supported data rate is 250kbps while the 2.4GHz ISM frequency band is divided into 16 channels.

Telos revB and Imote2 nodes integrate different micro-controller units. Telos revB uses the low-power 16-bit TI MSP430, while the Marvell PXA271 utilised by Imote2 is characterized by larger resources (in terms of memory, mips, É) at the cost of a higher average energy consumption.

5.6.2.2 WiFi Platforms

Considering instead the second class, *i.e.* the nodes for (multiple) WiFi connectivity, there is still a wide range of available platforms, which can be used for instance as prototype nodes of vehicular (opportunistic) network, to trace vehicular mobility integrating a GPS receiver, and /or to build an open flexible wireless mesh networks.

The simplest and more flexible solution (from the software and configuration point of view) is to build wireless nodes based on common PC platforms. If they are equipped with one or two PCI-to-miniPCI adapter it is possible to have from one to eight different interfaces on an unique device. Typically wireless mini-PCI are 802.11a/b/g based on Atheros chipset and working with madwifi [106] driver.

Moreover it is quite simple to act on the software router configuration (queues, routing prtocols), especially if the PC runs a Linux OS, to integrate higher layer (e.g. application layer) solution for opportunistic connectivity, to mount innovative Layer 3 open source protocol (such as MPLS) and to integrate a GPS receiver (for instance to trace experimentally the mobility of a node). The disadvantage instead would be energy consumption, dimensions, stability, indoor-only

To counter these limitation the solution can be to use some emergine, however already diffused embedded platforms, usually referred to as "routerboards" based on a processors (ARM, MIPS, PowerPC) mounted on a PCB with a series of different communication interfaces (Ethernet, serial, GPIO).

The wireless side is typically agnostic: one or more $mini_{PCI}$ slot that could be filled with any wireless communication technology. Many type of miniPCI are sold on the marked starting with the most famous like WiFi and WiMax, ending with proprietary implementation of WiFi over non-ISM bands.

So it is possible to build mesh networks with one or more wireless interfaces, even using heterogeneous technologies.

The core of this devices is some flavour of the Linux operating system that permits sharp configuration of many parameters and the availability of thousand of network specialized software: most of the devices are driven by openWRT [107] an open source operating system based on Linux and specifically created for this type of nodes.

Also with router boards it is possible to adapt well-established wired mechanisms (MPLS, queue management) to wireless communication and also to develop and test new paradigms related with opportunistic network research: the nodes are typically equipped with a certain (low) amount of volatile memory that could be used to store packets whilst some of them as the opportunity of mounting flash card.

5.6.3 Research challenges

In the following, we describe the experimental JRA tasks: the first one is based on ZigBee protocols, while the other three on WiFi; the first two ones are centered on opportunistic network examples, while the following ones on complementary aspects (collection of data of mobility and best configuration of existing infrastructure towards the opportunistic network).

5.6.3.1 Task 1 - Case study: WSN as opportunistic network

One of the most recurrent opportunistic network class is that of WSNs: they embody most of the features which have been mentioned for the paradigm of opportunistic networks.

Using the hardware devices described in 5.6.2.1 research activities will focus on the performance evaluation of network scenarios, possibly involving node mobility through simple mobility pattern capabilities. The experimental activities are meant also to validate theoretical results, facing problems, such as energy consumption and indoor propagation, in practice.

Typical metrics for the analyses will be based on parameters such as delay, throughput, goodput and channel capacity: they will be used to evaluate network performance under varying conditions (the environment in which nodes are deployed, the number of WSN nodes, the distance between them and their real mobility pattern, the protocols implemented in their stack, mainly at network and application layers) and to study and compare different routing protocol solutions.

An additional proposed JRA (to be confirmed) concerns the analysis of the issues (effectiveness) about the mutual opportunistic inter-working between WSN and an other network, such as a VANET, used to collect WSN data. This activity can benefit and merge the results of Task 1 and Task 2.

5.6.3.2 Task 2 - Case study: VANETs as opportunistic network

An other relevant class of opportunistic network is that of vehicular nodes. This widely studied with a pure theoretical approach, but most of the studies are intrinsically limitative because:

- they are based on pure theoretical mobility models and simulations;
- they are often set in highway or simplified urban scenarios;
- they often neglect real-life propagation issues (such as urban canyon, interferences or other EMC issues).

For this reason it is particularly interesting to

1. build a vehicular node, based on the PC platforms described in 5.6.2.2, integrating one ore more WiFi interfaces to test V2V (Vehicle to Vehicle) and V2I (Vehicle to Infrastructure) communications;

2. test protocol exchange and the efficiency of communications in the VANET environment (considering the effect of real urban propagation and issues such as mutual mobility, speed, ...).

These are then the objectives of the task, which is then useful to validate and perhaps extend variables to the results on performance of opportunistic networks achieved by the other JRAs.

5.6.3.3 Task 3 - Mobile platform for vehicular mobility tracing

This task , as the previous one, includes an integration action, an experimental activity and, hopefully a mixed practical and theoretical activity

1. The first objective is to extend the platform defined in the previous task, including also a GPS receiver: this HW/SW integration activity is meant to enable the tracing of car mobility to feed the mobility modeling JRAs.
2. The following activity and goal is just the experimental tracing of one or more cars, using the deployed platform (previous item).
3. Finally, if some aggregated data on traffic can be recovered among the partners (for example number of car passing a crossing in a certain period), a practical-theoretical activity may investigate how such data can be reverse engineered to get mobility traces for simulations. This too is promising to improve the mobility models of cars and to make more realistic vehicular simulations.

5.6.3.4 Task 4 - Case study: wireless mesh network as backbone of opportunistic networks

As already discussed in the introduction, opportunistic networks can exploit some form of infrastructure. More in detail this may happen under two different cases:

- Routing based on a fixed infreastructure: in this case there is a base station and the opportunistic connection is gained on the base station or on a station which acts as “bridge”.
- Routing based on mobile infrastructure: some mobile nodes act as mobile data collectors.

In both cases, whenever there is an infrastructure or at least a mobile infrastructure, having a protocols which can effectively allocate band on the wired/wireless infrastructure to allow data exchange in the seldom intermittent periods of connectivity, may raise the efficiency of the communications.

For this purpose a JRA of WPR.11 concerns the experimental study of the configuration of scalable protocols which can embody this function.

Using the PC platforms described in 5.6.2.2 it is possible to build a full mesh wireless network and to study strategies to assign the opportunistic traffic the appropriate QoS degree by acting on parameters such as IEEE 802.11e parameter, IP schedulers, OLSR routing protocols or MPLS configuration of linux nodes.

5.7 Coding in opportunistic networks

PARTICIPANTS: CNIT-CT (WPR11) and *TUM (WPR5)*

5.7.1 JRA definition

The research proposed under this JRA is targeted to study the applicability of network coding in the context of geographic routing.

In traditional networks, coding is used for two different purposes. At source nodes source coding is applied for data compression and therefore reduction of the required transmission bandwidth. On the other hand, channel coding is used at the link level to ensure reliable communication, thus enabling us to model links as essentially error-free channels subject to the channel capacity. Traditionally, intermediate nodes in a network were restricted to merely routing or replicating information. We speak of *network coding*, when intermediate nodes perform mathematical operations on the incoming data streams to obtain the output.

On the topic of geographic forwarding, several techniques have been proposed. The simplest strategy for performing geographic data delivery is simply forwarding the packet to the neighbour node that is closest to the destination. It is worth pointing out that the majority of the above schemes lack in integration between MAC and routing. This feature instead represents a key factor when designing approaches customized for sensor networks where the simplicity of the procedure, as well as the effectiveness in energy management, are required.

The research conducted in this JRA will be more focused on analyzing the usage of network coding in scenarios characterized by multicast transmissions.

More specifically, let us consider a scenario where static nodes exchange some data packets throughout the network. We assume a certain source node S wants to send a packet to a multicast group.

While in the work [108], authors assumed existence of an underlying connected graph where no interference among simultaneously sending nodes was met, we propose to exploit a mechanism like MACRO [93] to select time by time the best next relay which can allow to improve packet's progress towards the destinations. This mechanism will take into account both a simple MAC mechanism to reduce collisions at the medium access level and a routing algorithm. For what concerns the kind of data processed by nodes, intra-session random network coding can be used according to the approach proposed in [108].

5.7.2 Open Issues/Goals

Use of a more realistic and not collision-free MAC and routing protocols pose many problems in terms of:

- End-to-end delivery probability.
- End-to-end delivery delay.
- If nodes are mobile this can additionally decrease performance, consequently, the impact of mobility should be estimated.
- What is the decrease in performance when comparing no MACRO combined and MACRO combined approaches?
- It would be nice if we could design an algorithm specifically thought to allow proper multicast data forwarding through exploitation of both network coding and MACRO functioning. This algorithm should be optimized to give some guarantees in terms of delivery probability.

5.7.3 Workgroup organisation

The network coding background of TUM and expertise in terms of routing and MAC layer protocols of CNIT-CT can be combined to investigate a more realistic scenario and estimate the impact of mobility on system behaviour.

The research conducted in this JRA could be organized into the two temporal phases.

- Phase 1: Design of an algorithm exploiting both network coding and MACRO functionalities in static networks.
- Phase 2: Impact of mobility on the system's performance.

5.8 Opportunistic spectrum access

PARTICIPANTS: UPC (WPR11) and *CNRS-Supelec, CNIT-BO, CNRS-Eurecom (WPR9)*

5.8.1 JRA definition

The research proposed under this JRA is targeted to study the applicability of Opportunistic Spectrum Access (OSA) concepts and techniques in the context of wireless mesh and ad-hoc networking. OSA is a dynamic spectrum access model aimed at improving spectrum utilization by allowing more services/users to share the same band according to a hierarchical access structure with primary and secondary users. Hence, the basic idea is to open spectrum licensed to primary users to secondary users while limiting the interference perceived by primary users [109]. This approach does not necessarily impose severe restrictions on the transmission power of secondary users, but rather on when and where they may transmit so that services of the primary users are not disturbed. The concept of OSA was first envisioned by Mitola [110] under the term spectrum pooling and then investigated by the DARPA Next Generation (XG) program under the term OSA.

Nowadays, the applicability of the OSA model is being investigated in many different contexts. Hence, standardization activities in IEEE 802.22 are pushing for the OSA model in the way to build wireless access networks to provide services such as broadband Internet access in low population density areas (5-10 users/km^2) where other access technologies (wired or even other wireless technologies) may not be economically feasible. In particular, IEEE 802.22 will allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used and so exploit the good characteristics of those bands for achieving long-range non-line-of-sight broadband access. In a very different context, the usage of OSA is also proposed to solve spectrum congestion problems in high density 802.11 wireless LAN deployments. For instance, a potential application scenario is pointed in [111] in the context of Wireless Mesh Networks (WMN). In such scenario, 802.11 wireless cards are considered as secondary users of a given set of channels located around 700 Mhz so that some mesh access routers within the WMN are tuned to operate in a non-intrusive manner in those channels so that channel congestion in the common 2.4GHz band can be alleviated.

The research conducted in this JRA will be more focused on analyzing the usage of OSA in scenarios related to wireless mesh and ad-hoc networking where the concept of "opportunism" already constitutes an intrinsic and foundational attribute that impacts over different network functional aspects, being one of them the selection of a suitable operating frequency band.

5.8.2 Open Issues/Goals

In a first phase of our research, we propose to identify a set of relevant application scenarios and uses cases where the usage of OSA could lead to improved performance for ad-hoc networking. The definition of an application scenario will be formulated in terms of different aspects such as the type of application/service required by ad-hoc users, the envisaged primary bands, the transmission characteristics and mobility patterns of the primary users, etc. From such scenarios, a list of functional requirements to be considered when developing and analyzing OSA techniques will be derived (e.g. requirements related to primary users protection).

As from identified scenarios and related requirements, different components of an OSA solution are going to be analyzed for a given set of most relevant scenarios. In this sense, basic design components of OSA may include a (1) spectrum sensor at the physical layer for opportunity identification, (2) a sensing policy at the medium access control (MAC) layer for real-time decisions about which channels in the spectrum to sense, and (3) an access policy, also at the MAC layer, to determine whether to access based on the sensing outcome [112]. These three components should be designed to address some specific needs of secondary users (e.g. maximize the throughput by load balancing interference between primary and common bands) while limiting the interference to primary users. Some of the key open issues to design such OSA components are pointed out hereafter.

The spectrum sensor capability of a secondary user is aimed to detect the presence of primary signals and hence decide or contribute to the identification of spectrum opportunities. The sensing capabilities of network nodes can be very diverse, ranging from terminals which have specific hardware resources (e.g additional wireless network card) devoted exclusively to spectrum sensing without disturbing normal operation, to terminals that only can take advantage of inactivity periods during normal operation to perform sensing in different frequency channels. On the other hand, the availability of some kind of cognitive pilot channel broadcasted by an infrastructure network (e.g. cellular network) can also be considered as a potential information source regarding spectrum usability in a given space-time zone for ad-hoc networking purposes.

Regarding sensing policy, its purpose is usually twofold: catch a spectrum opportunity for immediate access, and obtain statistical information on spectrum occupancy for better opportunity tracking in the future. In ad-hoc networking scenarios, there may be no central coordinator or dedicated communication/control channel so that it could be necessary to develop decentralized MAC protocols where each secondary user independently searches for spectrum opportunities without relying on cooperation among secondary users. On the other hand, the deployment of cooperative sensing strategies among network nodes to improve detection capabilities along with decision fusion and robust decision making are important open issues to be addressed in those opportunistic ad-hoc networking scenarios. As well, the need for detection schemes that sense the spectrum continuously or just check primary activity periodically over a longer time scale depends strongly on the usage characteristics of the primary bands (e.g. presence of inactivity patterns in primary signals, mobility of primary users, etc.). All these aspects will determine the requirements to be imposed on the spectrum sensing policy of individual network nodes in an ad-hoc networking scenario.

Finally, as for the access policy, its basic objective is to minimize the chance of overlooking an opportunity without violating the constraint of being non-intrusive. Among the main open questions to be addressed in ad-hoc networking scenarios are the consequences of dealing with partial spectrum monitoring, the non negligible occurrence of sensing errors, and the development of techniques to maintain synchronization [1] between nodes with minimal overhead in terms of control message exchanges. Hence, one of the major design challenges is to coordinate and cooperate in accessing the spectrum opportunistically while mainly relying on local information [113].

5.8.3 Workgroup organisation

This JRA within WPR11 is aimed at exploiting synergies with some tasks carried out in WPR9 in the context of advanced spectrum management. In particular within WPR9 two activities have been identified so far:

- WG4: Measurements to detect spectrum availability. Partners: *UPC, CNRS-Supelec*.
- WG5: Cognitive Radio Network based on Sensorial radio bubble. Partners: *CNRS-Supelec, UPC, CNIT-BO, CNRS-Eurecom*.

In such a context, scenarios analysed under WPR9 are more related to infrastructure-based radio access networks while scenarios to be covered under WPR11 are more focused on ad-hoc networking".

[1] When a secondary user hops in the spectrum, seeking opportunities that are time-varying and location-dependent, its intended receiver needs to hop synchronously in order to carry out the communication.

6 CONCLUSIONS

In this deliverable we have reported the state of the art of research on opportunistic networks and definition of a common framework for reference models and performance metrics.

Specifically:

- We have provided a taxonomy of opportunistic networks and we have identified two main research trends.
- We have identified the characteristic and properties of opportunistic networks.
- According to the two research trends identified, we have presented the main research issues to be investigated inside the JRAs for the next three years.

Concerning the JRAs identified, we have planned the following activities:

- Opportunistic localization and tracking.
  - Partners: **CNIT-PD**, *CNRS/LAAS, RWTH, ISMB*.
  - The aim of the JRA is to devise, design and analyze novel opportunistic schemes aimed at enhancing the self-localization and tracking functionalities of some mobile nodes in a given area.
- Mathematical modeling of intermittent behavior in opportunistic networks.
  - Partners: **NKUA/IASA**, *CNIT-CT*.
  - The main objective of this research activity is to study the aspects of intermittent dynamics in opportunistic networks.
- Routing in opportunistic networks.
  - Partners: **CNIT-CT**, *CNRS/LIP6*.
  - The aim of this JRA is to design and analyze novel schemes and algorithms to improve routing efficiency (throughput, energy consumption, etc.) in opportunistic networks.
- Peer-to-peer techniques in opportunistic networks.
  - Partners: **Bilkent/KHAS**, *ISMB, CNIT-CT, CHAL/KAU*.
  - The intent with this JRA is to investigate how different P2P techniques can be used in Opportunic Networks and to investigate the design and issues of P2P systems/application over opportunistic networks.
- Opportunistic Connectivity: the Impact of Nodes Mobility.
  - Partners: **CNIT-BO**, *RWTH*.
  - The aim of the JRA is to introduce and analyze novel scenarios for wireless ad-hoc and sensor networks.
- Experimental activities.
  - Partners: **ISMB** - *CNIT-TO* - *CHAL/KAU*.
  - The aim of this JRA is to provide some results obtained through experimental activities in the context of opportunistic networking.
- Coding in opportunistic networks.

  - Partners: *CNIT-CT (WPR11)* and *TUM (WPR5)*.
  - The intent with this JRA is to create an algorithm specifically thought to allow proper multicast data forwarding through exploitation of both network coding and geographical routing.

- Opportunistic spectrum access.
  - Partners: *UPC (WPR11)* and *CNRS-Supelec, CNIT-BO, CNRS-Eurecom (WPR9)*.
  - The research proposed under this JRA is targeted to study the applicability of Opportunistic Spectrum Access (OSA) concepts and techniques in the context of wireless mesh and ad-hoc networking.

It is worth mentioning that some other research activities have been identified and proposed but they have not activated yet as JRAs, and therefore their description will be reported in the next deliverable. They are the following:

- Transport Layer issues in opportunistic networks.
- Fundamental throughput limit in opportunistic networks.
- Horizontal activity on the Resource Description Language Framework.

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