Opportunistic Networking as a Paradigm to Exploit Mobility

Invited Paper

S. Palazzo, A. Leonardi
CNIT
Catania Research Unit, Italy
spalazzo,aleonardi@diit.unict.it

M. Boc
UPMC
Univ. Paris 06, France
mathias.boc@lip6.fr

C.F. Chiasserini
CNIT
Torino Research Unit, Italy
chiasserini@polito.it

R. Verdone
CNIT
Bologna Research Unit, Italy
rverdone@deis.unibo.it

ABSTRACT

Recently, a new communication paradigm has imposed in wireless communications, which exploits *opportunism* as a means for exploiting the resources of separate network systems according to the needs of specific application tasks. In this paper, we describe the main characteristics of opportunistic networks and the most relevant research challenges they pose, highlighting how mobility can be both a threat and an advantage to be exploited.

Categories and Subject Descriptors

C.2 [**Computer-Communication Networks**]: Network Architecture and Design

General Terms

Algorithms

Keywords

Opportunistic Networks, Research Challenges, Mobility

1. INTRODUCTION

It is commonly acknowledged that user devices in the not-too-distant future will more and more resemble a communication hub, sporting arrays of GPS navigators, web browsers, videogame consoles and screens flashing the latest news or local sightseeing information. In this context, most pieces of information are likely to be of general use, and therefore a sensible dissemination and caching policy would be desirable. Unfortunately, several environments provide only spotty connectivity that make communication among the user devices a difficult task.

Mobimedia 2008 July 7-9, 2008, Oulu, Finland.
 ISBN 978-963-9799-25-7/08/07
DOI 10.4108/ICST.MOBIMEDIA2008. 4115

Recently, a new communication paradigm has imposed in wireless communications, which exploits *opportunism* as a means for information exchange and content delivery, when it is not possible to create or maintain an end-to-end path between source and destination. More specifically, the so-called opportunistic networks aim at jointly exploiting the resources of separate network systems according to the needs of specific application tasks.

In this context, two main research trends appear to be the most relevant: (i) the formation and management of Delay Tolerant Networks (DTNs) [3] and (ii) the *oppnets* paradigm for emergency preparedness and response [12, 19].

A *Delay Tolerant Network* (DTN) is defined as a network of *regional networks*, each of which relies on its own protocol stack and whose nodes use the same type of communication mechanism [3, 24]. A DTN is therefore an overlay which supports the interoperability of regional networks, and may be characterized by intermittent connectivity, long or variable delay, asymmetric data rate, or high error rate. Examples of DTNs include [3]: Terrestrial Mobile Networks, Non-conventional Media Networks, Tactical Ad Hoc Networks, Sensor/Actuator Networks. The characteristics of DTNs are clearly different from common telecommunication networks where a continuous and bidirectional path between the source and destinations is typically assumed. Examples of applications of Delay Tolerant Networks include Pocket Switched Networks (PSNs) [8], Autonomic Networks [6] and Socio-Aware Community Networks [22].

The second category of opportunistic networks, named *oppnets*, are ad hoc networks where diverse devices, not originally employed as nodes of an oppnet, join it dynamically to perform certain tasks they have been called to take part in [12]. 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. As an example, it might happen that the resources available in the seed oppnet are not sufficient to accomplish the task; thus, 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 can be successfully applied for distributed computing, sensing and networked actuators, as well as for emergency situations and homeland security.

A relevant issue characterising opportunistic networks is the need to establish a standardised language to describe the context and the resources available at each node, or network partition. In fact, resources of any type (mobility, spectrum, energy, memory, etc.) can be efficiently exchanged and opportunistically used only if information on their availability is periodically broadcast by nodes, regardless of the type of air interface used. Though relevant, this aspect is out of the scope of this paper.

In the remainder of this paper, we describe the main characteristics of opportunistic networks and the most relevant research challenges they pose, highlighting how mobility can be both a threat and an advantage to be exploited.

2. BASIC CONCEPTS

We provide here 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.

2.1 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 [7].

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 [3]. 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.

2.2 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.

- *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.

2.3 Characterizing the User behavior and the Network Topology

To characterize the system behavior, the following metrics can be introduced [13]:

- *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 users 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.

2.4 Assessing the Network Performance

To evaluate the performance of algorithms and protocols designed for opportunistic networks, the following metrics should 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:* The buffer occupancy at the network nodes;
- *Latency of a message:* The time between the instant 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:* The probability that a random message has a latency smaller than a certain time;
- *Path length:* The number of hops through which a packet has to travel before reaching its destination.

2.5 Models and Tools

Below, we list some models and tools suitable for representing the behavior of opportunistic networks [9].

- Models based on expectations of how mobility is performed in specific situations, such as campus and vehicular mobility models.
- Models tweaking Random WayPoint (RWP) parameters with specific distributions in order to yield more realistic results.
- Mobility measurements performed both indoor and outdoor.
- Mobility simulators, such as SIMPS [16]. It 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.
- Synthetic traces collected by using Second Life [13]. 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.

2.6 Reference network scenarios

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

- *Dancing room:* People equipped with small communication devices, likely using short-range technologies such as Bluetooth. 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.
- *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).
- *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.

3. RESEARCH ISSUES

In this section we discuss the main research issues in opportunistic networks, with particular attention to node mobility, traffic routing and resource allocation.

3.1 Mobility characterization

The analysis of spatial mobility is a relevant aspect in a wide range of domains (populations migration, geographic information science, transportation, wireless networking, and so on). Typically, the analysis of spatial mobility allows to develop enhanced mobility models, improve location and mobility management, and make mobility predictions. 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 adopted method, the raw data traces can be treated as they have been obtained or, an intermediate level with the purpose to hide tracking effects or to interpret the mobility patterns that can be alternatively used. In the following, we first describe the methods proposed to transform raw patterns into a succession of places and paths, then we discuss the mobility models based on observed mobility characteristics.

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" [10]. 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 easier to consider the mobility trajectory as composed by "places", i.e., areas where the cumulated pause duration is long enough to be distinguished as important for the node, and a number of "paths" connecting the different places. Note that an outer loop on the same place can be considered as a path as well.

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

With regards to the problem of places detection, the literature is rich of proposals [25] However, most 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 the different methods are about the choice of the clustering algorithm and the technology used to obtain the visited locations (and then the accuracy level induced).

The analysis of mobility behaviors leads to the identification of major common characteristics with the purpose of proposing mobility models that closely resemble real data traces, collected by tracking devices in wireless local-area networks or in cellular networks.

A possible approach to characterize the node mobility is first to detect places of interests (hotspots, concentration points, etc.) and then to understand how a node moves between them. Another method consist in considering 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. As an example, in [11] 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 a node at a give location will make a transition to a certain destination.

The characterization of mobility is often context-specific. Despite the increasing number of publicly available data traces, they come, most of the time, from the same type of context. Also, it is typically difficult to perceive how the environment of analysis and the tracked devices can have an influence on the observed mobility. Finally, in almost all studies, there is a real concern about how raw data traces have been filtered. As an example, consider that in wireless networks the devices' behavior can introduce ping-pong effects (i.e., succession of associations/disassociations between two or more APs); this behavior can significantly mislead the characterization of node mobility of the nodes.

We therefore observe that there is still a lot of work to be done to characterize the node mobility in opportunistic networks, with the necessary accuracy and in the different network environments.

3.2 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), it is clear that the network protocols must be adapted to 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 between devices that come into each other's radio proximity due to their mobility pattern.

Concerning the state of the art in the area of routing protocols, two possible criteria can be used to classify the various proposals appeared in the literature. The first criterion is related to the type of network, i.e., with and without infrastructure [14]; we can therefore have (i) routing algorithms that exploit infrastructure, and (ii) routing algorithms designed for networks without infrastructure. The second categorization is based on the evolution of the network [23]. 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. Accordingly, we have two categories of routing protocols: (i) routing protocols belonging to the deterministic case, and (ii) routing protocols belonging to the stochastic case. We point out that 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.

Finally, it is worthwhile mentioning an interesting class of protocols, which take into account the context where nodes operate to identify the best next hop along a source-destination path. They can be conveniently applied to networks both with and without infrastructure.

3.2.1 *Routing algorithms that exploit infrastructure*

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 former is the Infostation model [4], which is an example of direct communication between node and base station. The latter allows the communication between 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 (see for instance the SWIM scheme in [14]).

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) [20], 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. Another approach is DakNet, developed by MIT Media Lab researchers, [15]. DakNet 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.

Obviously, mobility can be exploited to improve performance in sensor network scenarios as well. In this case, networks are composed of tiny and battery powered devices, and reducing the nodes energy consumption is a major concern. As proposed in [23], the DataMule concept can be successfully applied to sensor networks to decrease energy consumption and, hence, increase the network lifetime.

3.2.2 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 the following.

Routing protocols belonging to the deterministic case. In the networks based on infrastructures (even fixed or mobile) as those described before, the nodes trajectories are known (or predictable) with high probability. For this reason, in this class of networks, more than in the networks without infrastructure it is convenient to apply the routing protocols belonging to the deterministic case.

As an example, in the tree approach [23], the routing algorithm selects the path for message delivery according to the available knowledge of the nodes motion. This approach, however, assumes global knowledge of the nodes mobility patterns, with respect to space and time. Most of the times such an assumption does not hold.

In [17], the authors introduce four knowledge categories called *oracles*; each oracle represents a certain knowledge of the network. Based on the available oracles, the routing algorithms act differently. Clearly, the larger the number of oracles available, the more accurate the routing decisions.

In Model Based Routing (MBR) [14], 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 such a user profile is an open issue.

A recent interesting work that takes into account human mobility is SocialCast [2], 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 mentioned above, 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 to address this issue.

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

In the Epidemic Routing category [18], 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 [5]. 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 in the network.

The *Spray and Wait* protocol [14] outperforms the flooding based routing schemes by reducing the number of copies that can be transmitted per single message. Message delivery is performed 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 the 1-hop neighbors of 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 decreases.

Another set of protocols belongs to the coding-based routing class. In particular, it is possible to classify erasure-coding routing protocols and network-coding routing protocols [14]. In erasure-coding routing, an original message is encoded into a large number of smaller code blocks. Protocols belonging to this class are pretty robust against packet losses due to bad channel condition, and they can result very energy efficient (depending on the compression factor).

In order to improve the performance of erasure-coding approaches, in [23] a combination of erasure coding and estimation-based forwarding is discussed. 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 [21]. 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 by running the decoding process. The advantage of this approach is that the number of message transmissions is reduced, and consequently the packet delivery ratio results much higher than the probabilistic forwarding even in dense mobile networks than in sparse networks.

3.2.3 Context-based routing protocols

Protocols shown before simply forward packets to either all neighbors or some of them. Unfortunately, this approach requires a huge amount of bandwidth and storage capacity and can result very energy inefficient. In order to improve performance, some routing protocols take into account the context in which node operate.

For example, in PROPHET (Probabilistic ROuting Protocol using History of Encounters and Transitivity) [14], 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 and on the history of visits to certain locations. Simulation results show that PROPHET outperforms epidemic routing in terms of both delivery success rate and delay.

In MobySpace Routing [14], 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 that the contact occurs. It is worth remarking that this approach requires the knowledge of the number of nodes in the considered space.

Another approach is the Context-Aware Routing protocol (CAR) [14]. In this protocol, two approaches for message delivery have been considered. For each node, when a packet arrives, if 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 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 obtained show that the delivery ratio of CAR is higher than epidemic routing.

3.3 Novel scheduling, resource allocation and MAC schemes

Scheduling and resource allocation are terms used with different meanings in the literature. It is therefore worth introducing some general definitions first.

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 quality of service. The RRM may be either centralized or distributed.

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) may be scheduled.

The *resource allocator* maintains a record of the (still) available resource budget and non-scheduled users/flows.

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. 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.

The kind of opportunistic network we have referred to as “oppnets” 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 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 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 other kind of opportunistic network we have referred to as DTN 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.

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.

4. CONCLUSIONS

This paper gives an overview of the main research challenges in opportunistic networks. In particular, we have provided some details on the architecture, characteristics and requirements of opportunistic networks. Also, we have described the performance metrics of interest, the reference network scenarios and some tools that can be used to study the performance of opportunistic networks. Finally, we have identified the main open research issues in the area of mobility characterization, routing strategies and resource allocation.

5. ACKNOWLEDGMENTS

This work was supported by the European Commission in the framework of the FP7 Network of Excellence in Wireless COMmunications NEWCOM++ (contract n. 216715).

6. REFERENCES

[1] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, J. Scott. Impact of human mobility on the design of opportunistic forwarding algorithms. *Proc. of IEEE Infocom,* Barcelona, Spain, Apr. 2006.

[2] P. Costa, C. Mascolo, M. Musolesi, G.P. Picco. Socially-aware routing for publish-subscribe in delay-tolerant mobile ad hoc networks. *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 5, pp.748-760, June 2008.

[3] K. Fall. A Delay Tolerant Networking Architecture for Challenged Internets. *Proc. SIGCOMM*, Karlsruhe, Germany, Aug. 2003.

[4] D. Goodman et al. Infostations: a new system model for data and messaging services. *Proc. IEEE Vehicular Technology Conference*, vol. 2, pp. 969-973, May 1997.

[5] M. Grossglauser, D. Tse. Mobility increases the capacity of wireless ad hoc networks. *Proc. of INFOCOM*, Apr. 2001.

[6] `http://www.haggleproject.org`.

[7] C.-M. Huang, K.-c. Lan, C.-Z. Tsai. A survey of opportunistic networks. *Proc. of AINA*, GinoWan, Japan, Mar. 2008.

[8] P. Hui, A. Chaintreau, R. Gass, J. Scott, J. Crowcroft, C. Diot. Pocket Switched Networking: Challenges, Feasibility and Implementation Issues. *Proc. of WAC*, Athens, Greece, Oct. 2005.

[9] A. Jardosh, E. Belding-Royer, K. Almeroth, S. Suri. Real world environment models for mobile ad hoc networks. IEEE Journal on Selected Areas in Communications, vol. 23, no. 3, Mar. 2005.

[10] M. Kim, D. Kotz, and S. Kim. Extracting a mobility model from real user traces. *Proc. of the 25th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM).* Barcelona, Spain, Apr. 2006.

[11] R. Hariharan, K. Toyama.Project Lachesis: Parsing and Modeling Location Histories. *GIScience*, pp. 106-124, 2004.

[12] L. Lilien, A. Gupta, Z. Yang. Opportunistic networks for emergency applications and their standard implementation framework. *Proc. of IPCCC 2007*, New Orleans, USA, Apr. 2007.

[13] C.-A. La, P. Michiardi. Characterizing user mobility in Second Life. *Technical Report.* RR08212, Institut Eurecom, Sophia Antipolis, France.

[14] L. Pelusi, A. Passarella, M. Conti. Opportunistic networking: Data forwarding in disconnected mobile ad hoc networks. *IEEE Communications Magazine*, vol. 44, pp. 134–141, Nov. 2006.

[15] A. Pentland, R. Fletcher, H. Hasson. Daknet: Rethinking Connectivity in Developing Nations. *IEEE Computer*, vol. 37, no. 1, pp. 96-107, Jan. 2004

[16] SIMPS: Sociological Interaction Mobility for Population Simulation, `http://www-rp.lip6.fr/~borrel/SIMPS/`.

[17] J. Sushant, K. Fall, and R. Patra. Routing in a delay tolerant network. *Proc. of SIGCOMM'04*, Aug. 2004.

[18] A. Vahdat, D. Becker. Epidemic routing for partially connected ad hoc networks. *Tech. Rep. CS-2000-06*, Department of Computer Science, Duke University, Durham, NC, 2000.

[19] R. Verdone, Environmental Opportunistic Networks (EONs) - a Concept Paper, COST2100 TD(08)450, Wroclaw, Poland, Feb. 2008.

[20] J. Yang, Y. Chen, M. Ammar, and C. Lee. Ferry Replacement Protocols in Sparse MANET Message Ferrying Systems. *Proc. of IEEE WCNC 2005.* New Orleans, USA, Mar. 2005.

[21] J. Widmer and J.-Y. Le Boudec. Network Coding for Efficient Communication in Extreme Networks. *Proc. of the ACM SIGCOMM 2005 Workshop on delay tolerant networks*, Philadelphia, USA, Aug. 2005.

[22] E. Yoneki, P. Hui, S. Chan, J. Crowcroft. A Socio-Aware Overlay for Publish/Subscribe Communication in Delay Tolerant Networks. *Proc. of MSWiM*, Crete, Greece, Oct. 2007.

[23] Z. Zhang. Routing in Intermittently Connected Mobile Ad Hoc Networks and Delay Tolerant Networks: Overview and Challenges. *IEEE Communications Surveys and Tutorials*, vol. 8, no. 1, pp. 24-37, Jan. 2006.

[24] Q. Zhang, Q. Chen, F. Yang, X. Shen, Z. Niu. Cooperative and opportunistic transmission for wireless ad hoc networks. *IEEE Networks*, vol. 21, pp. 14–20, Jan.-Feb. 2007.

[25] C. Zhou, D. Frankowski, P. Ludford, S. Shekhar, and L. Terveen. Discovering personally meaningful places: An interactive clustering approach. *ACM Trans. Inf. Syst.*, vol. 25, no. 3, Jul. 2007.