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Jani Kurhinen

Information Delivery in Mobile Peer-to-Peer Networks

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ABSTRACT

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Personal mobile computers and smart communication devices as well as embedded intelligent hardware are part of the current way of living. This technology has been used to provide local stand-alone applications and wireless network services. However, short-range connectivity, which has already been an existing part of devices for several years, has only recently gained popularity in a wider scope.

This thesis studies information transmission in a mobile peer-to-peer network. In particular the thesis focuses on information diffusion from one source to a population of mobile nodes and information collection from several sources to one sink node using mobile peer-to-peer network nodes as information carriers.

The contribution of the thesis consists of three parts: 1) A mathematical model for information diffusion in mobile peer-to-peer networks. 2) Introduction and formal definition of a mobile encounter network. 3) A method for information routing within a mobile peer-to-peer network.

The models and methods presented in this thesis can be used as a basis when designing applications that rely on information diffusion or intelligent data routing. Additionally the thesis provides a discussion on possible future application scenario of mobile peer-to-peer networking.

Keywords: Mobile peer-to-peer, Information diffusion

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Jyväskylä November 15, 2007,
Jani Kurhinen

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PI J. Kurhinen, M. Vapa, M. Weber, N. Kotilainen, and J. Vuori. Short Range Wireless P2P for Co-operative Learning. In *Proceedings of the 3rd International Conference on Emerging Telecommunications Technologies and Applications: Information and Telecommunications Technologies in Education (ICETA 2004)*, pages 141-145, 2004.

PII J. Kurhinen, and J. Vuori. Information Diffusion in a Single-Hop Mobile Peer-to-Peer Network. In *Proceedings of the 10th IEEE Symposium on Computers and Communications (ISCC 2005)*, pages 137-142, 2005.

PIII J. Kurhinen, and J. Vuori. MP2P Network as an Information Diffusion Channel. In *Proceedings of the 62nd IEEE Vehicular Technology Conference (VTC Fall05)*, pages 2307-2310, 2005.

PIV J. Kurhinen. MP2P Network in Collecting Data from Delay Tolerant Sensor Networks. In *Proceedings of the 11th IEEE Symposium on Computers and Communications (ISCC 2006)*, pages 246-250, 2006.

PV J. Kurhinen, V. Korhonen, M. Vapa, and M. Weber. Modelling mobile encounter networks. In *Proceedings of the 17th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2006)*, pages 1-4, 2006.

PVI J. Kurhinen, and J. Janatuinen. Geographical Routing for Delay Tolerant Encounter Networks. In *Proceedings of the 12th IEEE Symposium on Computers and Communications (ISCC 2007)*, pages 463-467, 2007.

PVII V. Korhonen, and J. Kurhinen. Information Exchange in Mobile Encounter Network. In *Proceedings of the The Third International Conference on Networking and Services (ICNS07)*, 6 pages, 2007.

PVIII J. Kurhinen, and J. Janatuinen. Delay Tolerant Routing in Sparse Vehicular Network. *Acta Electrotechnica et Informatica, in press*, 8 pages.

The author has participated in the writing process of all the listed publications. Below is a short description of the articles and the author's contribution on the content of the papers.

Publication **PI** introduces a mobile learning environment, in which content can be shared between mobile terminals using short-range connections. The author introduced the idea of using Mobile Chedar middleware in this context. In publication **PII** the author presented the original idea of focusing on the information diffusion process instead of the mobility of network nodes. The paper introduces the exchange pipe model to describe the information diffusion process. In publication **PIII** the author presented additional results which were found when studying information diffusion using the exchange pipe model, and especially the effect of utilizing MP2M technology. In publication **PIV** the idea of modelling information diffusion with the exchange pipe model was reversed in order to describe information collection from several sources to one sink node. The simulation environment used in publications **PII**-**PIV** was designed and implemented by the author. Publication **PV** introduces a concept of mobile encounter networks. The author defined the mathematical model for MP2P encounters, and thus provided the encounter networks with a formal definition. Publication **PVII** continues discussing mobile encounter networks. The author provided the idea of using different mobility models to describe behaviour of mobile nodes in different parts of the simulation environment. The author also participated in planning the simulation settings and evaluating the results. Publication **PVI** and **PVIII** discuss MP2P nodes as delay tolerant networks. In **PVI** the author introduced the idea of smart messages which route themselves by monitoring movement of mobile data carriers. In **PVIII** the author defined the framework for the paper and planned requirements for the simulations.

ACRONYMS

C/S	Client/Server
C2C	Car-to-Car
C2I	Car-to-Infrastructure
DTN	Delay-Tolerant Network
MANET	Mobile Ad Hoc Network
MEN	Mobile Encounter Network
MP2P	Mobile Peer-to-Peer
P2P	Peer-to-Peer
PDA	Personal Digital Assistant
PIM	Personal Information Manager
VANET	Vehicular Ad Hoc Network
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle

1 INTRODUCTION

The importance of mobile computing increases continuously. Personal digital assistants (PDA) and voice centred mobile phones have become powerful application platforms which are used in almost all fields of modern society. In addition to a wide spectrum of applications that can be used with these devices, they are able to be used for creating new data: one can, for example, contribute to a live blog or share photographs with the world immediately after they have been captured. The created data has been transmitted mostly using cellular or wireless local area networks, but also via short range wireless data links. Napster, Gnutella and other peer-to-peer communication systems have taught people to utilize this new communication paradigm in both entertainment and business. Peer-to-peer computing using short range connectivity is still in its infancy. However, the idea of harnessing millions of mobile terminals to provide all imaginable content to information consumers is intriguing.

This thesis discusses a system which is a combination of smart mobile communication terminals, ad hoc networking, wireless short range data links, nomadic network nodes, and the peer-to-peer communication paradigm. Information transmission in such a system is a complex process. Since we do not have this type of technology available on a large scale yet, the only way to forecast its possible applicability is by using abstract models and simulations. Simulations of a system that does not exist is, however, challenging and is based on assumptions, intuitions and expectations.

The objective of this thesis is to create a model for describing a system that utilises mobile network nodes for delivering data in a peer-to-peer community. It is assumed that the mobile nodes use wireless short-range connectivity for communication. The delivered data can be directed to a known receiver or broadcasted to a set of network nodes.

The research aimed at finding a new type of model began five years ago, in 2002. At that time the mobile peer-to-peer networking studies concentrated on modelling random movement of the mobile nodes and the possibilities for them to route data within such an environment. The initial need for this thesis was to create a model to describe information diffusion in a system that was more systematic than the existing settings based on free random movement.

The traditional way of routing data from a source to a destination via intermediate nodes was already found to be difficult in a complex system which topology was highly dynamic. Various routing algorithms were presented in literature, but another approach was made for this thesis: multi-hop routing was abandoned in favour of mobility assisted single-hop information delivery.

After the model was created, a new research problem emerged: How can an MP2P system be used for data collection. The original simulator for observing information diffusion was reprogrammed and the process was reversed into information collection using an epidemic routing, one hop from a data source to a mobile carrier and the next hops to the encountered nodes or to the destination. In the third phase the multi-hop ideology was re-established with the addition of smart messages finding their destination by themselves. As a result a new routing algorithm was introduced. At this point we had studied information spread, gathering and transportation in the context of mobile peer-to-peer networking.

The rest of this thesis has the following structure. The next chapter discusses the background of the studied system. It gives a brief review of communication paradigms, and focuses on mobile peer-to-peer networking: What is it? How does it work and where can it be applied? In the third chapter we discuss modelling. The chapter starts with mobility modelling and continues with communication modelling. The chapter ends with a discussion on the results. The last part of the thesis consists of reprints of eight articles which are the results of the research that has been done.

2 MOBILE PEER-TO-PEER NETWORKING

The way machines communicate with each other can be modelled with three communication paradigms: *Client/Server*, *Push* and *Peer-to-Peer*. Before continuing with mobile peer-to-peer networking, all the paradigms are briefly introduced.

Client/server (C/S)is the traditional way of data communication. In this model a server possesses some data elements that a client is interested in. In order to acquire the desired elements, the client sends a *request* to the server. The server reacts to the request with a *response* in which it delivers the requested data, or some other information if the requested data is undeliverable. Therefore, we can say that this paradigm is a *reactive* communication method.

Push model is the second of the older and traditionally used methods. Similarly to the C/S model, it also has a client and a server device, but in this method, as the name implies, the data is sent without any particular request, i.e. it is pushed and this is *proactive* communication method. When comparing the actual data delivery between C/S and push models, one of the biggest issues is related to the targeting of data to the client. In the C/S model the client sends a request and includes information where to deliver the response. The push method, on the other hand, must rely on some other mechanisms when setting the target information: it can use, for example, broadcasting or previously stored address information. The data reception is, however, prone to failures, since there are less guarantees compared to the C/S model that there actually is a client device ready to receive a transmission.

With both C/S and push models there is a specialized data container unit that provides data to those wishing to consume it. The peer-to-peer (P2P) model, on the other hand, consists of a set of machines who can all act either as a data provider or data consumer. At a micro level, where one observes only one communication transaction, a typical P2P communication resembles the C/S model: a data consumer requests content from a data provider who returns the applicable data, and thus this is also a reactive communication method. On the other hand, if someone within the P2P communication system wishes to spread information it possesses, it can follow the push model. The ideological difference is that there

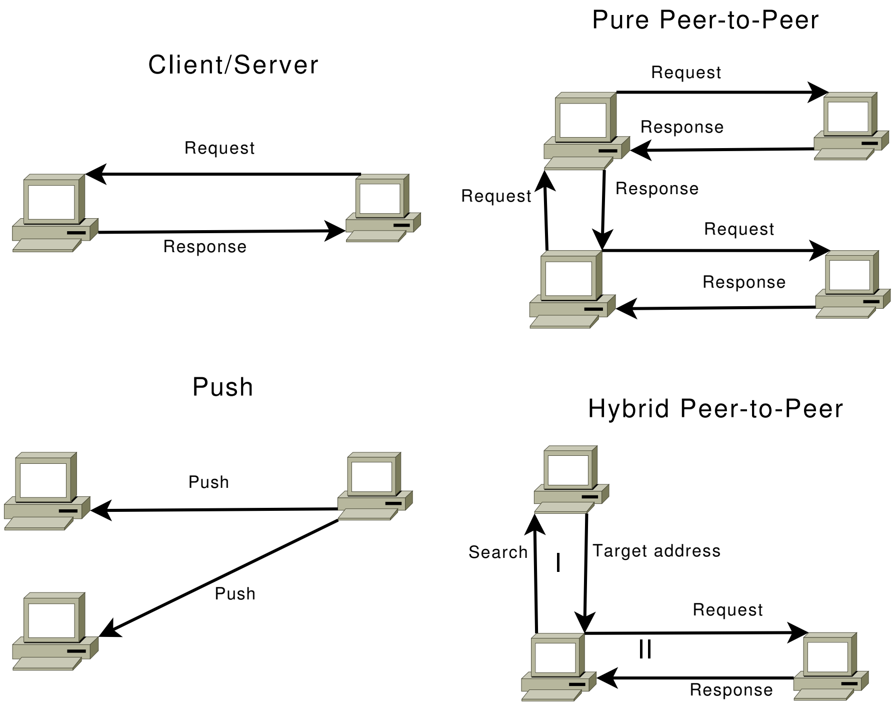

FIGURE 1 Communication paradigms.

are no particular data providers or data consumers, but all the networking nodes might be able to act as such. Therefore the majority of the networking nodes are no longer passive information consumers, but they have become active parts that can respond to other nodes' needs [45].

In fact, the dualistic role of the nodes is the main reason for public interest in the P2P systems. The Peer-to-peer network can harness resources scattered over the network environment much better than any of the traditional models. Parmeswaren et al. [45] makes a note that with P2P system the network is no longer only a mandatory functional component, but it is a source of resources, and P2P systems concentrate on utilizing those resources. Network users have applied the peer-to-peer networking paradigm eagerly, but they have also found the weakness of the system's distributed nature. The plenitude of data stored all around the network makes it difficult to find some particular piece of data. In a C/S system, there is a known source of data to which a request must be sent, but the P2P paradigm does not have such a single source. In order to create a solution to the data location problem, there have been proposals for the technology that is something between C/S and P2P.

Since the P2P technology is relatively young, the terminology is not yet fully stabilized. Nakamura et al. [39] and Oh-ishi et al. [42] uses the terms pure P2P and hybrid P2P to describe the different approaches. On the other hand, Walkerdine et al. [57] call them fully distributed and semi-centralized respectively. The pure or distributed peer-to-peer system only contains equal network nodes, and follows the P2P paradigm presented above. In the hybrid or semi-centralized P2P network there are also some special nodes which provide indexing services.

When the actual peers inform the special nodes that they have some resource to be shared, it is easy for a data consumer to search the content from the indexing server and then request the data from its provider. Figure 1 presents a summary of the communication paradigms.

2.1 Ad hoc networks

In the 1970's the US *Defense Advanced Research Project Agency* (*DARPA*), *US army* and *US Office of Naval Research* (*ONR*) created a technology in which mobile troops were not dependent on one single command unit, but units were able to communicate with each other without any predefined chain of communication. The technology was called *Mobile Packet Radio Networking* and it was defined as a collection of mobile platforms forming a distributed network which can operate without any help of other infrastructure except the units themselves [32]. Today the technology is called *Mobile Ad Hoc Networking* (*MANET*).

The principle idea behind MANET lies in multipurpose network nodes which can communicate with each other. As stated above, this communication must take place without any external help: This includes a situation where two communicating nodes do not have a direct radio link with each other. In order to be able to communicate without the direct link, the data transmission must be delivered via other intermediate nodes (Fig. 2).

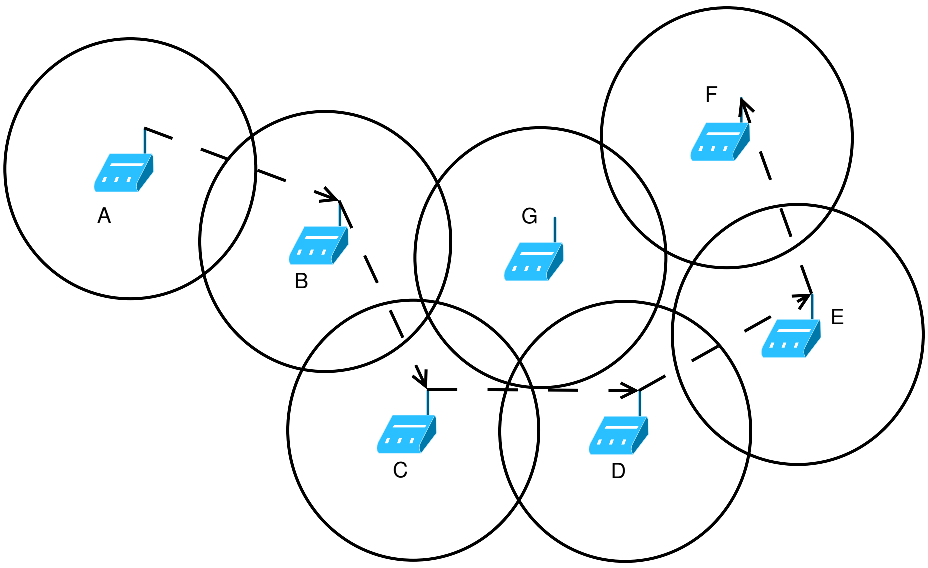

FIGURE 2 Data transmission in ad hoc network.

As can be seen from Figure 2, the message that node A sends to node F, must be delivered via several other network nodes which do not participate in the actual communication. In the figure the message was routed via nodes B,C,D and E, while the shortest, and possibly the optimal, path would have been via nodes B and G. The reason for making the decision to use the longer route may have been caused by an insufficient knowledge of the network topology (node A does not know the location or existence of node G) or sudden change in the topology (node G may have just entered its current location). Delivering the message to the target node is, in fact, one of the most critical problems related to MANETs. An article [10] lists the current efforts of the *IETF MANET working group*, which includes a goal of having one *reactive* and one *proactive* routing protocol to be used in the scope of MANETS.

Reactive routing takes place on demand and it only keeps track of the routes of immediate interest [46]. With this routing method the changes in the network topology and possible routes between network nodes are not updated on a regular basis, but a requested route is solved when needed.

Proactive routing, on the other hand, has full knowledge of the state of the network and is aware of all possible routes [46]. The biggest advantage of such routing protocols is the minimal initial delay in the communication transaction, but this comes at the expense of network-wide additional control traffic that is required in order to deliver topology changes to the nodes.

Both routing methods are applicable in a scope of ad hoc networking. The one that should be used depends on the scenario: If the topology within the ad hoc system remains fairly stable, the minimal initial delay of proactive routing is an advantage. However, if the topology is dynamic, the proactive method would cause substantial overhead, and therefore the reactive method should be used. In a general case both methods share a common feature: a message is transmitted via intermediate network nodes to its destination and, as already mentioned, there are no specialized routing nodes, but every single node needs to act as an intermediate node if required. In this sense ad hoc networking resembles P2P communication. However, data delivery via other nodes should not be classified as such: The intermediate nodes only establish a communication channel between communicating nodes, which in turn can utilize any of the three communication paradigms.

In addition to the actual routing problem, ad hoc networks also suffer from other typical characteristics of it. Fall [18], for example, lists the following: interruptions in communication, heterogenity of network elements, reliable end-to-end data delivery, security and quality of service. Due to the mentioned issues, he uses a term *challenged internet*.

2.2 Mobile P2P

The previous sections introduced both the peer-to-peer communication paradigm and the ad hoc networking scheme. When comparing these two technologies with each other, one can find certain similar features. First, there are no central units which control the system. Secondly, the topology of the system is dynamic and prone to continuous changes. Despite the similarities, it is crucial to understand that these two technologies operate on different layers of the networking stack: Peer-to-peer communication is an application layer functionality whereas ad hoc networking deals with low level layers, from physical to network layer [16]. The combination is called *mobile peer-to-peer* (*MP2P*) and it is under heavy research at the moment.

Even though these two technologies share similar features, combining them is not necessarily straightforward due to the reason that they deal with different network layers. Since the traditional P2P protocols operate on an application layer, they do not have any knowledge of the networking layer properties, and therefore they can not know whether they are used in a fixed or wireless network environment. A network failure, for example, which is very likely to happen in a MANET system, would require a reconnection process. In a fixed environment it would be a good choice to retry the same node, but with the MANET environment this might not be the best link anymore, but it would require a new routing decision [49].

Taking into account the specific characteristics of both P2P communication and ad hoc networking, Charas [11] describes MP2P using the following three aspects: 1) True multi access. There can not be any requirement for an access medium. This means that mobility is not related to any single access technology, and is not even tied to wireless ones. 2) Transport independence for services. This requirement is a result of the first one, but also adds independence of a transport protocol and emphasizes freedom to choose any suitable access medium. 3) Identification for services and users must be available without any centralized control management system. Thus it leaves all the responsibility for defining required authentication methods to the end user. Currently there are some technologies, like digital certificates stored on smart cards that can be used to provide such services.

The P2P paradigm in a mobile environment is attractive, since it offers the means to harness the increasing resources of mobile terminals. Currently we are in a situation where communication speeds and energy consumption still limit the possibilities that peer-to-peer networking could provide for mobile users. However, despite the limitations, if the number of mobile users reaches a certain limit, the MP2P networking concept can provide more advantages than costs it requires [34]. The number of MP2P users was an important parameter in **PII** and **PIII**. In addition to other contribution these papers discuss the effect of participating users on the information diffusion process.

2.2.1 Communication

This thesis discusses information delivery within a MP2P system, and it focuses on two approaches: 1) information diffusion from one source to a set of MP2P nodes, 2) information collection from several sources to one target using MP2P nodes as carriers. As was previously pointed out routing through intermediate nodes within such a dynamic system is challenging. When observing data transmission more closely, we can find two opposite cases: reactive, on demand data transmission and proactive data transmission which actively participates in the

TABLE 1 Information delivery in different environments.

	Transmission type	
Communication method	Single hop	Multi hop
Reactive	Query from a known source	Routing in a dynamic environment
Proactive	Data exchange between encountering nodes	Routing in a stable environment

communication process. Even though the methods use different approaches, a common characteristic, and actually the source of the complexity, is a need to utilize other nodes than the communication parties. However, the whole communication system is simplified by only allowing direct links between a source and a target node. When limiting communication to a single-hop instead of using intermediate nodes and multi-hop routing, the possibilities of such a system might seem rather limited. However, as Spyropoulos et al. [53] has said "mobility can be turned into a useful ally".

In publication **PV** we introduce the concept of mobile encounter network, MEN. The main idea behind the concept is the same as the one cited above. In MEN environment, data is transmitted only during node encounters. One encounter contains a discovery of devices, the establishment of a connection between two devices and the exchange of data. Instead of being a cause of problems, mobility of the nodes provides a method for data delivery from one node to another. The actual mobile encounter network is a result of all the encounters and data exchange. When studying a communication system like MEN, it can be noted that network nodes are able to create short-term connections with several other network nodes i.e. a network topology can be defined as a function that is dependent on time. Due to the continuous changes in the network topology, nodes may end up inside a communication range of other parties which posses the desired information or to which they want to deliver information.

In fact, prior to the introduction of the MEN environment, the mobility of network nodes was already used to enable data delivery. Even though the main contribution of **PII** was in information diffusion modelling, the concept that was presented in it was also based on mobility of the network nodes as a data routing method.

Table 1 which was presented in **PV** illustrates data delivery in different environments. In addition to the traditional multi hop data transmission, the table also contains a single hop transmission. As can be seen from the table, when we talk about multi hop transmission, we are always facing the problem of finding a path from one node to another, i.e. a way of routing data. On the other hand, single hop communication is tied with direct needs of individual network nodes. As an example of a reactive single hop scenario is a case where a node finds its way to a place where it knows some data exists, like requesting payment instructions from an automated parking meter. In addition, we face a proactive single hop transmission when a node looks for some certain piece of data, but does not know the source for it or is not able to move to the source location. In this case the only possible solution is to request the data from other nodes.

2.2.2 Routing

The previous section introduced the single hop communication, which can simplify the situation in some cases. However, it does not suite all the communication systems. The single hop method can only be used with applications that can tolerate certain delays. In general these types of systems are called delay tolerant networks, DTN [17]. On the other hand, DTNs can not only rely on direct node to node data delivery, but in many cases they can benefit from multi hop routing. Data MULEs [51] is one of the very first concepts describing this kind of environment, in which data was routed using several independent mobile carriers. Our studies in **PIV**, **PVI** and **PVIII** discuss similar network systems, where data is collected from several sources to one data sink. The data was collected and transported by mobile entities that were already moving within the environment, and therefore the delivery would not cause additional costs. The multi hop transmission was, indeed, the most practical approach in this case: Instead of giving full responsibility to one of these mobile entities to deliver the data packet to its target location, it was possible to pass the data to another unit which, in turn, might be able to transmit the data to the actual receiver.

The multi hop routing algorithms can be divided into three classes: 1) Epidemic spreading, 2) Epidemic spreading with limitations or restrictions, and 3) targeted data delivery. Epidemic routing was introduced by Vahdat and Becker [56]. As the name implies the algorithm works like a disease: using epidemic routing, messages are passed to all possible network nodes in the hope that someone is able to deliver it to a target location. In fact, it is a really powerful method and always gives the smallest delay if the network system handles the data flow properly. The same thing that makes epidemic routing so efficient also makes it extremely heavy on the system. While copying the messages to other network nodes, the epidemic algorithm wastes plenty of system's resources like storage capacity, radio time and power. As was pointed out in **PVIII**, for example, relatively soon after the release of the data, the whole network population is infected by it.

The second class of multi hop routing aims at reducing the disadvantages of epidemic spreading by setting some kind of limitations to the number of copies or trying to stop the spread as soon as the data has found its way to the receiver. Harras et al. [19] has studied different approaches to limit epidemic diffusion by controlling the number of retransmissions and preventing epidemic spread with acknowledgement messages they called a cure. The message receiver sends a cure when the first copy arrives. Cures heal the epidemic by erasing the original messages as they spread into the network. A similar idea was presented in [22]. A request message was sent using epidemic spreading, but the response traffic was limited. Moreover, Spyropoulos et al. [52] has proposed Spray and Wait and later

Spray and Focus [54] protocols, which are other methods to limit the epidemic diffusion. Spray and Wait exploits the different types of counters to control the number of copies in the network. Spray and Focus is the second evolution version, which combines copying and forwarding. These schemes, however, do not make the effort of selecting between distinct nodes while passing on message copies. Instead, they employ numerous randomly selected nodes as message carriers, although the Spray and Focus protocol tries during the focusing phase to take advantage of potential opportunities to forward the message closer to its destination.

The third class of multi hop routing protocols can be described as being more intelligent than the two previous classes. Opposite to random spreading these methods focus on selecting an appropriate carrier node among the contacted nodes, and to keep the messages themselves if there are no better carriers. An obvious method to route a message is to send it via nodes which form the shortest path. This would, however, require information about the topology of the network. As mentioned before, information about the topology, and therefore the optimal path, can be obtained reactively or proactively depending on the application scenario. In either way, both the sender and the intermediate nodes must know the route to the target, and this assumption is not always applicable. In some cases, like in city centres or on main roads, the possible message carriers, i.e. the networking environment, is extremely dynamic, and there might not exist any path between a sender and receiver that would be stable enough to enable data transmission if a valid path would be required.

One promising set of intelligent methods are location-based routing protocols. These protocols use geographic or direction information of both the mobile carriers and target location. Chen et al. [13] has proposed one idea in which they couple a store-carry-forward paradigm to localized geographical routing schemes. In their optimistic forwarding strategy, as they call it (also called opportunistic forwarding [29][59]), a message is forwarded closer to its geographical destination by selecting a node which has the smallest distance between a node's and the recipient's geographic location. The protocol selects the message carrier from all those nodes, which can be reached with one epidemic multi-hop query. Thus, it finds the closest node from a connected cloud regardless of the cloud's topology.

Another method, MDDV, was introduced by Wu et al. [59]. The idea was to disseminate messages between sender and receiver along a defined trajectory of a mobile unit. When compared to [13], this method takes advantage of different types of location information. In MDDV, nodes advertise the last known location of the most forwarded copy and the message carriers nearby that location form a group, which actively disseminates messages to encountered nodes. In addition, the protocols in [29] (MoVe) and **PVIII** (PGR) use not only the location, but also the motion of the carrier nodes. MoVe algorithm, relays messages to a node whose motion vector points closer to the message's destination. PGR, on the other hand, combines direction and the known trajectories (i.e. predictable mobility) of the nodes, and therefore it can avoid some of the problems of both pure direction based and predictable mobility based methods.

The second principle that has been studied as a basis for intelligent routing is to observe the social relations of the nodes. In some networks, routing protocols can benefit from the contact history of nodes by using it in order to predict future contacts. Contact history might reflect on the social aspects of the system. Thus, nodes encountering each other are more likely to encounter again in the future than the nodes that have never met each other. For example, proposals in [15], [30] and [36] are based on or closely related to contact predictions. Hui and Crowcroft [21] have taken this approach one step further and they have collected real empirical data on how data delivery within a group of socially equal nodes benefits from this approach.

Previous methods have discussed how the routing decision should be made. Another aspect is which component should take care of the decision making process. Traditional routing, which is a network layer issue, is considered purely as a system level functionality, and thus it is implemented as part of the operating system of the computing unit. There are, however, research papers, which have a different approach. In [6], **PVI** and **PIII** they are smart messages themselves who deal with routing. In these proposals the routing decision is moved from the system level to a user space into an application layer. The biggest benefit of this model is that the mobile carriers can remain purely carriers, and they do not have any additional responsibilities. The only thing that is required is a software component that can accept incoming smart messages.

2.3 Sensor networks

Sensor networks do not belong to the context of mobile peer-to-peer networking by definition, but they are one possible and interesting application area where MP2P might be used as a data transmission medium. Sensor networks are a collection of sensing, data processing and communicating components that can be used to monitor their environment in health care, at home or in military applications [1]. In addition to those, sensor networks are valuable in structural health monitoring [14], machinery condition-based maintenance [55] or in wildlife research [24]. Even though the sensing unit themselves have some processing power, there is also one (or many) more powerful central unit(s), which are used for analyzing data captured by numerous sensors.

When collecting sensor system data, the acquired information is normally transmitted via other nodes to this central location where it would be processed. However, the usage of intermediate nodes puts an additional load on the nodes along the route. Sensor systems are often self-organizing, i.e. have the ability to create an optimal topology on the fly [50]. After this organization has taken place, an individual node always functions in the same way: when it acquires information needed by the central node, it sends the data to the intermediate node, which then sends it on to another intermediate node or to the central node.

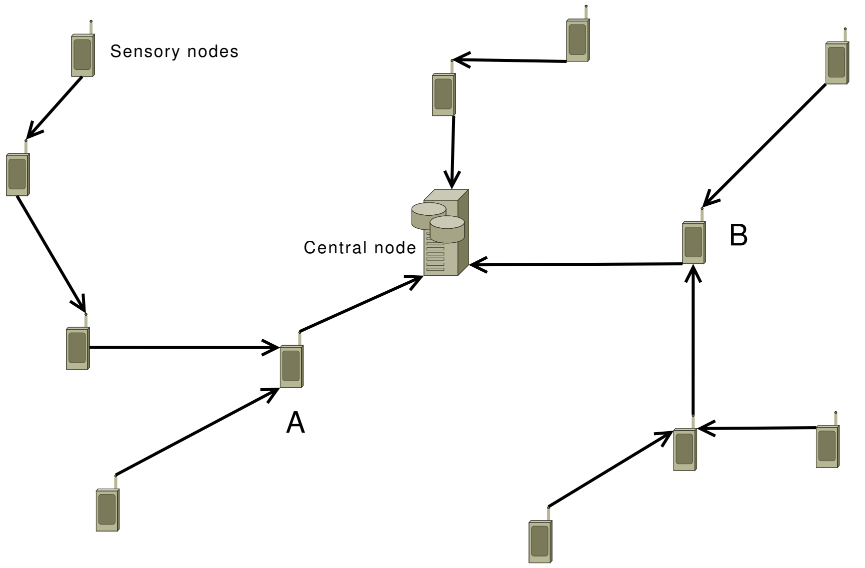

FIGURE 3 Sensors transmitting information via other sensors.

This is the case in Figure 3. It depicts this traditional way of collecting sensor system data. The smaller units representing the sensor nodes gathering information from their environment and sending it via routes represented by the arrows to the central node. When using the topology depicted in the figure, the intermediate sensor nodes A and B not only gather information themselves but also transmit all the information they get from other sensor nodes to the central node. This leads to the question that is maybe the most important research problem in the context of sensor networks: How to save energy to retain the sensors functioning for a long period of time without external power and maintenance?

Depending on the application scenario, both short- and long-range wireless communication links are used in inter-sensor communication [28], but only seldom is mere short-range communication sufficient. Long-range communication is, however, expensive in terms of energy consumption. It would be more efficient, if low-power short-range connectivity could be used, especially while the nodes should be able to function independently with many practical applications for long periods of time. This was a part of the research problem on **PIV**. In the paper it was noted that taking advantage of short-range connectivity and mobile data carriers, we can omit the requirement of having an energy consuming long range radio link. It was pointed out that transmitting a small number of copies with a short-range radio link to nodes visiting the communication range was enough to provide high probability of successful data delivery.

2.4 Network nodes

In the previous sections we discussed how the network nodes communicate and how it is possible to deliver messages from a sender to a receiver. We have used terms like entity or unit as representatives of those nodes. However, we have not yet defined who or what the actual mobile nodes could be. The purpose of this section is to lighten up the background for the question that why do we have this particular field of research.

A paper written by Arai et al. [2] is one of the very first publications which talks about information diffusion within a system that closely resembles MP2P community. Their paper is a study of a set of mobile robots which have some tasks to perform. The robots receive their instructions from fixed locations while moving in the area. After having received the instructions, a robot is able to forward it to another robot using *local communication*.The system is further analyzed in [64].

The robots, even though they might be used for several different types of tasks, they are not the real reason for MP2P research. Ludford et al. has written a paper [31], in which they have spelt out a phrase that well characterizes the background: *Because I carry my cell phone anyway*. The rise of mobile computing started in the early 90s, but at that time the main purpose of those devices was in personal information management (PIM) or in pure (voice) communication. It was the Palm phenomenon, when the Palm Pilot's markets grew faster than any other computing product in history[38], and the true mobile phones, which were small enough to be carried, that gave an initial impulse to the development that has created a need to study mobile computing as part of our everyday life. Furthermore, as the devices, and the technology behind them, matured, the portable communication machines became something more than just PIM or communication terminals. **PI** discusses an application scenario where personal mobile handheld devices could be used as a tool for co-operative classroom working.

Human carried devices are, in fact, one of the most important types of an MP2P system. A pocket Switched Network concept [20] was introduced to characterize a networking environment that would be based on a combination of human mobility, mobile computing devices and local wireless networking. In addition to pocket-sized computers that users are able to carry with them all the time, there is another technology that is also related to humans and is more ubiquitous. Wearable computing, i.e. smart electronics embedded, for example, in clothes, boots or eye glasses, is perhaps not yet a mainstream technology of today, but it is likely to be important in the near future. A proposed application with which wearable computing devices were harnessed to deliver data can be found, for example, in [15].

In addition to human carried computing devices the transformation of mobile phones and PDAs into powerful mobile computers and increasing the presence of powerful embedded devices have inspired, for example in [67], to take advantage of this new type of computing resource. In the paper, the researchers present an application for taxi reservation using local short-range connections, mobile handsets and ad hoc networking. The application, therefore, combines automobiles and humans to form one mobile ad hoc network.

An ad hoc network, which is formed of different types of vehicles, is another important set of MP2P network nodes. This kind of network has its own acronym

VANET. A research related to VANETs is still relatively young, which reflects in the terminology that is used. Within VANETs one can divide communication into two groups: communication between two vehicles and communication from a vehicle to its surroundings (or from surroundings to a vehicle). When discussing the first the authors of [60] and [47] use the term V2V (Vehicle-to-vehicle), and from the latter they use term V2R (Vehicle-to-roadside). On the other hand the terms C2C (Car-to-car) and C2I (Car-to-infrastructure) respectively are used in [7]. It seems, however, that the latter term pair is gaining position as a de facto standard.

A special case of VANETs for data delivery is the usage of public transportation systems as carriers. These types of network nodes offer a much higher utilization rate compared to private vehicles because of predictability of movement. One of the most cited papers discussing such an environment is written by Wang et al. [58]. They propose *Postmanet*, a system turning the postal system into a generic communication mechanism. Even though the proposal is rather impractical to implement, it has provided the basic element for newer research ideas like Cyber cars [7], which are city vehicles with fully automated driving capabilities. The Cyber cars use a C2C communication protocol which allows cooperation and information sharing between two cyber cars.

Humans and different types of moving vehicles can be equipped relatively easily with mobile computing devices, and therefore they are easy to consider as MP2P network nodes. [24] introduces a totally different environment which can exploit MP2P networking. The idea of ZebraNET was developed to monitor wildlife. A group of animals equipped with electronic collars operate as a P2P network to deliver logged data back to researchers. This is a good example of a combination of sensor networks and mobile peer-to-peer communication. A special feature with this particular sensor network was that the data sinks (i.e. the researchers) were also mobile.

3 MODELING MOBILE NETWORK COMMUNITIES

When studying a system like a mobile peer-to-peer network, often the first thing to do is to select a node mobility model best suited for the particular case. This approach is a good one if the aim of the study is to observe behaviour of nodes. However, this is not always the case, and another common target of research is inter-node communication. If the only target of the study is to estimate communication and data transmission processes, a simulation of the node mobility does not provide any added value if there is a suitable model for the communication process. This chapter discusses the both, modelling of the mobility and modelling of the communication. The chapter also presents the main contribution of this doctoral thesis and their relationship to existing studies.

3.1 Mobility

A mobility model is traditionally a starting point when studying mobile ad hoc systems, including VANETs, DTNs and MP2P networks. The models differ from each other in several characteristics, for example, a node direction selection, duration of continuous motion, and node behaviour near the border of the simulation area.

There are many possibilities to classify the different models. A common base for the classification is to use the division between synthetic and real mobility traces (also called statistical and deterministic respectively). In [8] the division is specified further into entity and group models. In [66] there is a minor addition to the traditional classification by dividing the models into statistical, constrained topology and trace based models. The first two are synthetic models, while the second does not allow total freedom of movement, and the last one is based on real mobility traces.

Another way to classify the models is to divide them according to the method of creating trajectories of nodes. This is the case in [5], where a class of hybrid mobility models was defined in addition to the traditional classes of models. A hybrid model would be a synthetic one, but it would be defined based on real world observations and not only on statistics. A similar classification is presented in [4], where a hybrid model was defined to have deterministic behaviour in either a spatial or temporal domain.

In this thesis the model classification is furthermore refined to consist of two major branches: *random mobility* and *trace based mobility*. Random mobility is statistical by nature: with these models a node selects a random target location, and finds its way there. If there are obstacles or rules for the movement, they must be respected. Therefore, even while the paths that the nodes move along are selected randomly mobility is not necessary totally random. The trace based mobility, on the other hand, relies on real paths that real world entities could actually use. The paths, or the traces, of the nodes are based on the observation of a real world scenario, but they do not have to be exactly the same. The simulation settings can contain different synthetic forms of the node trajectories with varying mobility parameters, like velocity and decision making at crossroads.

3.1.1 Random mobility

Abstract mathematical models are invaluable tools, because they can provide repeatable results and the possibility to adjust parameters to control output. They do not try to depict accurately the real world at an entity level, but they aim at simulating the system. Therefore, they can be used to achieve statistically sound results even though a mobility pattern of a single node might seem absurd.

The random walk mobility model is the simplest of the used mobility models. It mimics the Brownian motion where molecules freely and randomly vibrate in gas or liquid. An important characteristic of the random walk is that within a 2-dimensional space the node will return to its starting point with complete certainty. This feature can be used in scenarios where the mobility should take its place around the starting point and not to escape from the simulation space [8].

The Random waypoint model provides a small addition to the simple random walk: pause times between changes in speed or direction. With this feature the model reaches closer to a real world scenario by letting the nodes stand still. With the random walk model, the nodes are in constant motion. Due to the fact that the only meaningful differences between these two models are the pause times, the above mentioned characteristics and application scenarios are also valid for the random waypoint model. Figure 4 depicts an example path of a mobile node created either with the random walk or the random waypoint model. This model is the most popular when doing simulations with ad hoc networks. For example, Yoon et al. [61] noted that nine out of ten node mobility simulations in ACM MobiHoc2002 conference used this model. At the same time they were also worried about the behaviour of the model: It will take a lot of time for the model to achieve a state where average node mobility would be steady. They have shown that the model suffers from average speed decay, which will affect the results because the environment setting will vary. The problem is caused by an inevitable long slow duration velocity paths, during which the slow moving nodes skew

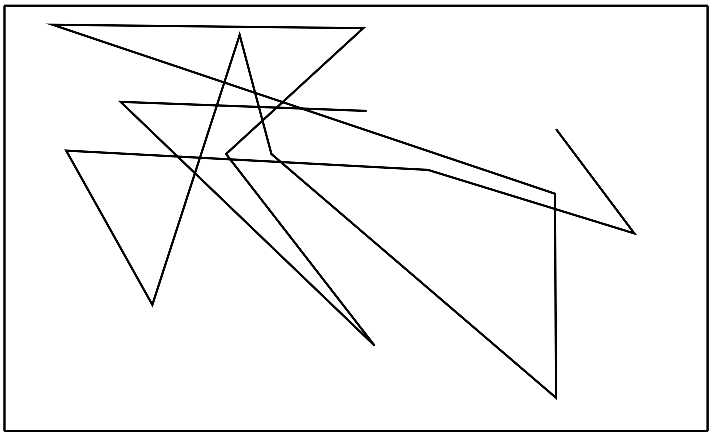

FIGURE 4 A node path of the random walk or random waypoint model.

the average speed of the system. By selecting a non-zero minimum speed will help reach a steady state earlier, but the problem will still exist.

The same research group, which already reported the speed decay problem of the random waypoint model, continued studying the phenomenon, and noted that any random mobility model that chooses its speed and destination independently from each other suffers from the same problem [62]. Yet another, already widely known problem of the above mentioned models, is an uneven spatial node distribution. This problem is caused by the fact that random selection of target positions using a uniform distribution of coordinates makes the nodes spend more time near the centre of the simulation space [8]. To achieve a more even nodal distribution Royer et al. modified the random waypoint model and created *the random direction* model [48]. Instead of selecting a target position, in this model a node selects a random direction, to which it continues until it reaches the boundary of the simulation area, and in this way it utilizes more areas near the edges compared to the other two older models.

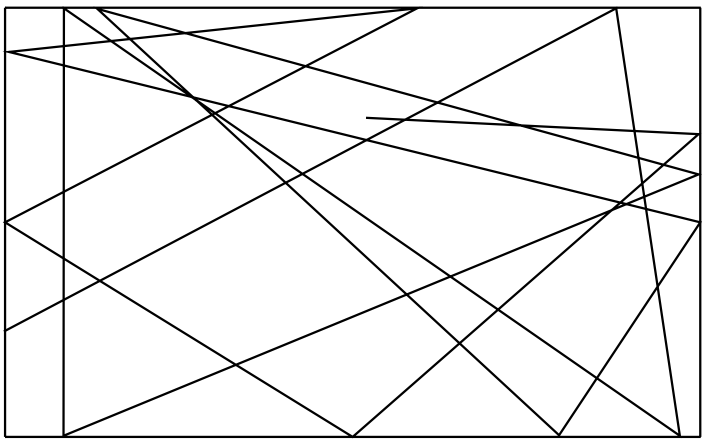

FIGURE 5 A node path of the random direction model.

As illustrated in Figure 5 the path of the node uses the simulation space more equally compared to the random walk or random waypoint models. Together with the random waypoint model, the random walk and the random direction models form the top three of the most popular mobility models used to study ad hoc networks [65].

In addition to the above mentioned three popular models, there are a number of other models which have the same basic setting: There is a simulation space (usually rectangular in shape) in which nodes freely move and change speeds and directions according to some algorithm. The models include additional characteristics like nodes appearing from the other side of the space when they hit the edge, avoiding sharp turns by remembering the old direction or selecting directions that would be the most probable [8]. A more noteworthy modification is the presence of objects that limit free movement. These kinds of models are, for example, *city section* [8], *Obstacle* [23], and *freeway* and *Manhattan* [3] mobility models. With these models the mobility is still random, but it is restricted to follow some pre-defined routes and to avoid some areas. The effect of such rules is an increased number of average neighbours and the encounter of other nodes.

To combine the advantages of both free and limited mobility models a new type of model was introduced in **PV**. The model was created according to an observation that node density of ad hoc network systems will vary in time and in space [26]. In the model two different characteristics were defined into one single model. We used the city section model to depict areas where a great number of nodes are located, and the random way point model to depict sparser areas. Nodes were able to change their position between the areas with a certain probability. **PVII** gives a more detailed specification of the model and the used parameters.

A completely different mobility model, *the pipe model*, was defined in **PII**. The pipe model was targeted on communication research using short range wireless communication, and it is even more statistical by nature than the existing random mobility based models. As was earlier pointed out, the traditional way of studying ad hoc networks has a tendency to always focus on modelling the movement patterns of mobile nodes. However, a MP2P network with a very limited communication range can not be expected to work, unless an adequate number of nodes are located in a limited area at a given moment. When this assumption is combined with the notion voiced in [26] that mobile nodes are typically packed in certain areas, it can be justified to change the focus of the study from separate mobile nodes to defined observation areas.

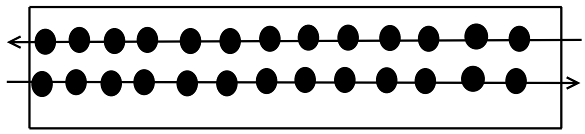

FIGURE 6 Pipe model.

Figure 6 depicts the pipe model. It focuses exactly on these relevant areas where information can be exchanged due to high node density. A simulation space consists of one or more pipes and a set of nodes. The core of the model is a pipe through which the nodes can travel. When a node enters the pipe, it has the possibility to interact with other nodes. Outside the pipe there is no interaction, i.e. a node can not obtain anything that would make a change in its state, and therefore no computational resources are needed to process them. The main characteristics of the pipe model are the possibilities for a chain reaction and pipes with different parameters (size, capable of interaction or not, number and speeds of node flows). The nodes are randomly selected to enter the pipe, and the implementation in **PII** made it possible to bias the selection in order to favour some subsets of the nodes. This feature reflects the behaviour of different types of nodes, from which some are more active in their movement than others.

3.1.2 Trace based mobility

The second set of mobility models in the scope of this thesis are models which are based on pre-defined paths that the nodes must follow. The paths can be synthetic or real traces, but even the synthetic ones are based on realistic mobility. The movement of the nodes along the paths, however, can be defined based on statistics. The nodes might change their speed or direction and they may need to make choices between possible routes. The selection of the next target and the pause times between two trips are adjustable as well.

This set of models provides the researcher with an accurate knowledge of events within a simulated system. Even though the result gained with these types of models should reflect the real world scenario with a greater reliability compared to the statistical models, they do not suite all the cases because of four main reasons [37]: 1) There is very limited amount of data available to generate the traces. 2) The models that depict their environment with great detail are not well suited for general use, because the achieved results reflect the particular environment. 3) Sensitivity analysis is not possible with fixed parameters. 4) These models are hard or impossible to be defined mathematically, which might be an important aspect in some type of analysis.

As noted above the models of this type do not usually have an exact algorithm according to which the mobility is generated. Research in this divides into two parts: how to obtain traces and how to make studies with them. Additionally, at some times researchers mix the concept of the mobility model with something else. In [40], for example, the authors introduce a "new mobility model for VANET". According to the paper, the new model is, in fact, merely a method where they use input from an external traffic simulator to a general purpose simulator (NS-2) that they have programmed for inter vehicular routing. The method itself is usable, but it is not a mobility model. Actually, the trace-driven simulations can be performed without any model just by using the recorded traces [27].

Compared to the previous example, the authors of [33] are much more careful with their words. They present a "method to generate a mobility scenario", while the method could be called a mobility model. The proposed method uses real world observations of node mobility as a starting point and generates imaginary routes that are sound in the sense that a real world node could travel along them. In their paper Kim et al. [27] use a similar method. In order to define a new mobility model they emphasize the importance of understanding the mobility as a process, and the need of being able to obtain detailed mobility data about real users and carefully characterize their mobility. When analyzing the mobility data, they searched regularities on characteristics like pause times, speed distribution and direction of movement. According to the result, the particular source material revealed mathematical regularities on pause times and speed distribution, but only context-related regularities on direction of movement.

A model based on student movement in a campus area was presented in [5]. As with the model in [27], the authors were also able to provide an analytical description for their model, although much more simple that was focusing only on probable directions. In addition to analyze fine-grained data collected from individual people to create a mobility model, Yoon et al. [63] introduce a method for refining coarse-grained data into a mobility model. They designed a model which combined geographical data (maps) with user information from wireless access points. The topology information from the maps was used to form user paths from the wireless access point logs using heuristics based on distance. The authors claimed that their model can be used to predict user densities on certain areas and probabilities for a user to follow certain routes, although the results did not provide 100 per cent accuracy. A pure trace-based model was introduced in [35], which also used a campus area as their environment. The authors criticized synthetic mobility models for not reflecting the real world characteristics. However, at the same time they were not able to see the down side of a "too realistic" model: there was no formal definition provided, the model setting was tightly related to the particular environment, and therefore, the environment parameters were not adjustable.

The location based mobility model used in **PVI** and **PVIII** is not similar than the others in a sense that it is merely a method for selecting the next target location. The method itself does not try to model the environment, but it only focuses on node behaviour. It can and should be used in conjunction with other models that generate the actual traces and important locations. In the *location-based mobility model*, each node has an individual location pattern containing several positions that the node visits frequently. The movement of the nodes takes place in a graph representing a road map, where nodes roam between their own regular visits or randomly selected locations which consists of a few locations representing shops and other favoured visiting areas which are preferred in a nodes location pattern.

3.2 Communication

When ad hoc and mobile peer-to-peer networking become attractive to the research community, most of the resources were targeted on overcoming the problems caused by mobility. Today the situation is different: mobility has been understood to provide new possibilities that were previously unavailable. One of these new possibilities is communication between nodes that only have a temporary, short duration point-to-point communication link. The previous section provided an overview of methods for modelling node mobility within mobile communities. However, in many studies where those mobility models were used, the main target was to study inter node communication, and the simulated mobility of the network nodes was only a tool for achieving results. In [25], for example, the authors stated that good mobility models should incorporate both user behaviour and the wireless link characteristics. On the other hand, studying the mobility in itself does not give us any added value if we are only interested in the communication process. This leads us to a conclusion that node mobility simulations are not relevant if the communication process itself can be modelled. In other words, understanding the effect of mobility provides us with a possibility to omit it from the communications studies.

3.2.1 Node encounters

The most obvious requisite for inter node communication is that they can establish a communication link. In the context of this thesis, the communication link is restricted to a short-range local communication. With this restriction in mind, we can say that node encounters are the only relevant events when studying communication in MP2P systems. It is especially important to analyze the frequency and duration of contacts between the carriers of communication devices [9].

This problem, however, has been studied only a little. **PV** is among the first published studies to describe the mathematical characteristics of node encounters. The paper discusses simulation settings that are aimed at finding regularities in node encounters. The dual mobility model was used to simulate mobility of the nodes, and the result was that successive encounters of two mobile nodes resemble gamma distribution. In [9] the authors have real data about human encounters. Their analysis revealed that power law distribution was the best approximation of the observed behaviour. They noted, however, two limitations in applying the formal method: a granularity of observations (i.e. how often the state of the system was recorded) limits the accuracy and long encounter intervals (more than one day) differed considerably from the observations. Another issue regarding the power law distribution is that the distribution function gets high output values with small values of the variable. Therefore, if such a distribution is used, one must be very careful when setting a domain for the observation. Even though our simulations in **PV** resulted in contact periods to follow the gamma distribution, the presented mathematical model was not tied to any particular distribution. In fact, the distribution of contacts characterizes the environment and therefore should be selected based on the best knowledge.

Neither of the above mentioned studies included duration of the encounters, but only a number and intervals. However, the authors of [12] remarked that these values do not say anything about how long each contact will last, and therefore they do not provide enough information about the possibility of actual data transfer. In addition, they reminded that if there is human behaviour involved, the dependency of contact should be taken into consideration. This type of social relations were used for an interaction study in [37]. In the paper the authors talk about the community based mobility model that takes human behaviour into account. They defined an interaction matrix to describe social relations of the community including the notion that social networks are time dependent, and can vary depending on the time of day or day of the week. With the help of the interaction matrix they generated a connection matrix, which was used to define whether the two nodes had connectivity or not. As a conclusion they noted that the introduced model reproduced contact information that has characteristics similar to real world observations, but they did not provide a formal definition.

3.2.2 Information diffusion

Mobility models can be used to simulate node encounters which, in turn, are basic elements for studying data spread. Information diffusion among mobile nodes within a mobile community was a starting point for a set of studies that culminate in this doctoral thesis. It has been studied earlier by, for example, Arai et al. [2] and Khelil et al. [26]. Both of these studies used some free random mobility model to generate a communication event between the network nodes. When studying information diffusion in a system, in addition to the model for mobility of the network nodes, there is also a requirement for modelling the information exchange process, i.e. the way a piece of information is transferred between nodes. One possible, and often used, model is an epidemic diffusion model. Although, the epidemic model is widely used in various areas of research, its main problem is its tight relation with random mobility models: it is assumed that an object which carries the 'infection' will meet other objects in a random pattern. When using this kind of model, the number of infected users as a function of time will have a general S-shaped form of the logistic function, like the ones from Arai et al. and Khelil et al. The same type of results have also been presented in a more recent paper [44], which discusses the spreading of computer viruses in a mobile ad hoc environment. The nature of the results are based on the fact that with only random mobility it requires 'critical mass on infected objects' for the information to spread quickly. Therefore at the beginning of the diffusion process the information spread is rather slow until it explodes.

As an opposite to this traditional model, we claimed in **PII** that information can be expected to spread faster immediately when it is released into an area where there is a high density of possible new carriers of the information. The results were achieved while using the pipe mobility model discussed in the Section 3.1.1. The results of similar nature was presented in [41]. In the paper a worm epidemic was modelled in a VANET environment. Many of the characteristics of the particular study were similar to our information diffusion study with the pipe model. The VANET environment that utilizes a road network provides a similar communication pattern between the nodes than our pipe model. In addition, the worm epidemic was released into a population dense enough. Therefore the spread of data could start from the beginning with full power.

In addition to mobile units only, Arai et al. [2] also included stationary information sources into their study. These source points were fixed locations where the spreading information originated. Similar extensions were also used in a study by Papadopouli et al. [43]. Although Papadopuli's study was not about information diffusion in a MP2P network, they also presented the idea of the need for stationary components to complement mobility models. In other words, one must take in account all the elements that might affect the result whether they are mobile or not. This and an assumption that not all of the mobile nodes are able to participate in an information diffusion process were implemented in **PII** where we provided a mathematical expression to the results.

When observing the simulation results more specifically we noticed that the curve of the simulation results resembled function

$$n(t) = P - Pe^{-kt}, \tag{1}$$

but it was not as smooth, and the parameters P and k could not be fitted to suite that function. However, from the output of the simulator one can separate three different factors: 1) The nodes that do not have technology for MP2P, and therefore are able to receive information only from the information source. 2) The nodes that have received their data from another node inside an exchange pipe. 3) The nodes which have the required technology, but received the information from the information source. The nodes who form the third factor act as a carrier and therefore they are the ones who start the explosive information diffusion process at the exchange pipe. By drawing the curves of these three factors separately we can see that each factor draws a curve that is in the form of (1) and it is possible to fit the parameters P and k to follow the simulation results. It can thus be argued that information diffusion in a short range mobile peer-to-peer network can be modelled with function *N(t)* as a sum of (1) with three different parameters:

$$N(t) = \sum_{i=1}^{3} n_i(t) = \sum_{i=1}^{3} P_i - P_i e^{-k_i t}, \tag{2}$$

in which P_i is the number of nodes in the group i and k_i are constants which values depends on environmental setting. The presented equation (2) provides a tool for predicting the data spread within a mobile community without running actual simulations. The only requirements are numerical values for the constants of the equation.

The model for information diffusion presented above is valid only when the node mobility of a system can be modelled using the pipe model. The pipe model, on the other hand, was designed to reflect city centers and other highly crowded places. In **PV** we introduced a concept of *Mobile Encounter Networks*, MEN, which is more general and can be used for environments with another type of a mobility pattern. The formal definition of the concept provides us with a tool for taking advantage of node encounters in order to model information diffusion. The definition is presented below:

Let us define B as a vector which maintains a state of n network nodes: whether they possess the information or not

$$B = [b_1, b_2 \ldots, b_n], \; b_i \in \{0, 1\} \;\; \forall \, i \in [1, 2, \ldots n]. \tag{3}$$

Further, let us define an encounter matrix

$$F = \begin{bmatrix} f_{1,1}(t) & \cdots & f_{1,n}(t) \\ \vdots & \ddots & \vdots \\ f_{n,1}(t) & \cdots & f_{n,n}(t) \end{bmatrix} \tag{4}$$

to indicate the possibility of nodes communicating with each other so that value 1 of the discrete and binary-valued function

$$f_{i,j}(t) \in \{0, 1\} \tag{5}$$

represents the possibility of communication from node i to node j. Because communication with oneself does not provide added value, let us define

$$f_{i,i}(t) \equiv 0, \; \forall \; i \in [1, 2, \ldots, n]. \tag{6}$$

Therefore, we can say that information diffusion taking place at time t will cause a change in the vector B, so that

$$b_i(t+1) = b_i(t) \bigvee_{j=1}^{n} \left[f(t)_{i,j} \bigwedge b_{j(t)} \right], \forall \; i \in [1, 2, \ldots n]. \tag{7}$$

Thus we can write that if

$$\tilde{B} = \left[\tilde{b}_1, \tilde{b}_2 \ldots, \tilde{b}_n\right] = B \times F, \tag{8}$$

then

$$b_i(t+1) = \begin{cases} 0, \; \tilde{b}_i = 0, \\ 1, \; \tilde{b}_i > 1, \end{cases} \;\; \forall \; i \in [1, 2, \ldots n]. \tag{9}$$

A set of functions (5), which are elements of matrix F, characterizes the information diffusion process with non zero values denoting a possibility to data exchange. In order to give a formulation to the data exchange possibilities, let us define

$$t_{k,i,j} \tag{10}$$

to represent the time when node i encounters node j for the k^{th} time. Thus we can say that function (5) is defined as follows

$$f_{i,j}(t) = \begin{cases} 1, \; t \in T = \left[t_{1,i,j}, t_{2,i,j}, \ldots, t_{m,i,j}, \ldots\right] \\ 0, \; t \notin T \end{cases}, \tag{11}$$

and the values of function

$$\tau_{i,j}(l) = t_{l,i,j} - t_{l-1,i,j}, \; l \in [2, 3, \ldots] \, \forall \, i, j \in [1, 2, \ldots n] \wedge i \neq j \tag{12}$$

is defined by the distribution of encounters. If the distribution is available, the MEN formalization contributes knowledge about information diffusion with the vector B in Eq. (3).

Information diffusion shares some characteristics with epidemic routing discussed in Section 2.2.2, but it is important to separate them from each other. Even though the mechanism is the same with both of them, the difference is that with epidemic routing a message is delivered to a predefined target location. Depending on the situation, there can be one (uni-cast) or several (multi-cast) targets. With an information diffusion process, a piece of data flooded to as large a set of receivers as possible (broadcast). In other words, uni-cast and multi-cast transmissions have a predefined targets, and broadcasting delivers data blindly to its environment. For example, MEN provides a push based solution for epidemic information spread rather than actual routing.

3.3 Discussion on results

In the thesis there were several contributions which considered information diffusion from one source to a population of mobile nodes, information collection from several sources to one target using mobile nodes as carriers, and information routing from one source to one destination using (several different) mobile carriers.

Let us consider the information diffusion function (2). The shape of the function is similar compared to heat conductivity in physics. The characteristics of these two phenomena share common features. In both cases there are two sets that are originally in different states and the system attempts to stabilize itself by letting particles move from a higher concentration to a lower one. The soundness of the results is further verified when compared to the results in [41]. Their simulation settings had similar characteristics and results were also analogous. Their analysis concluded that the data spread was linear when it was at its maximum. Let us now take the first order derivative of (2). As a result we will achieve a monotonic decreasing function:

$$\frac{dN(t)}{dt} = \sum_{i=1}^{3} P_i k_i e^{-k_i t}. \tag{13}$$

By letting (13) approach origin from the positive side,

$$\lim_{t \to 0+} \frac{dN(t)}{dt} = \sum_{i=1}^{3} P_i k_i, \tag{14}$$

we will see that it results in a constant value, i.e. the Function (2) has a maximum of linear growth which depends on the population and other environmental conditions.

The formal description of MEN does not provide any values or functions, but only an instruction in how to define the encounter matrix (4). By knowing the distribution of node encounters within a system, the element functions of the encounter matrix should be set so that the conditions of (11) and (12) are fulfilled.

If there is not enough information available of the MP2P system, the only solution to study communication is to simulate mobility of the nodes. Both the statistical and deterministic models have their pros and cons. On the one hand, deterministic models provide knowledge of the behaviour of the nodes. On the other hand, they are suited only for that particular or very similar environment. When using the statistical models, the best they can provide is an approximation of the results. However, the resulted approximation might be valid for a number of environments.

The third part of the major contribution of the thesis was the idea of letting smart messages route themselves. This concept provides dual layer mobility: At the lower layer the message carrier is mobile, and the message can take advantage of the movement of its host. At the higher layer, the smart message is also mobile. It will try to search for a new host, if the current one can not offer transportation service to a required location. As the method of describing information diffusion in MEN, the concept of self routing smart messages is also independent of the details. For example, any of the routing methods presented in Section 2.2.2 can be used.

Further studies should be made in order to be able to define accurate metrics for the presented models and parameter dependency on real world phenomena.

YHTEENVETO (FINNISH SUMMARY)

Henkilökohtaiset kämmentietokoneet, älypuhelimet sekä erilaisiin kulutustavaroihin sulautettu elektroniikka on osa nykypäiväistä elämää. Näitä järjestelmiä on käytetty joko itsenäisesti tai pitkän kantaman langattomien verkkojen välityksellä. Lyhyen kantaman langattomat yhteydet ovat aiemmin kuitenkin jääneet vähemmälle huomiolle, vaikka teknologia itsessään on ollut osa laitteita jo jonkin aikaa. Vasta viime vuosina on alettu tutkimaan lyhyen kantaman datakommunikaation tarjoamia mahdollisuuksia.

Tämä väitöskirja käsittelee informaation välittymistä mobiileissa vertaisverkoissa. Erityistarkastelun kohteina ovat informaation diffusoituminen yhdestä pisteestä mobiilipopulaation keskuuteen sekä informaation kerääminen useasta lähteestä yhteen pisteeseen mobiilisolmujen välityksellä.

Väitöskirja tarjoaa uusia menetelmiä kolmeen osa-alueeseen: 1) Matemaattinen malli informaation diffusoitumisesta mobiileissa vertaisverkoissa. 2) Mobiilin kohtaamisverkon esittely sekä sen formaali määritelmä. 3) Menetelmä informaation reitittämiseksi mobiilissa vertaisverkossa.

Kirjassa esiteltäviä malleja sekä menetelmiä voidaan käyttää suunniteltaessa sovelluksia tai palveluita, jotka hyödyntävät informaation diffusoitumista tai älykästä reitittymistä. Lisäksi työn tulokset tarjoavat lähtökohdan kokonaan uuden tyyppisten sovellusten kehittämiselle.

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