Efficient Connection Establishment, Message Handling and Content Delivery in Opportunistic Networks

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Abstract

Opportunistic networking has recently gained decent attention from the research community. Opportunistic networks in general are characterized by nodes with typically wireless communication capabilities that typically move around and have either no, a single or a few communication partners present. The network is considered as often being so sparsely populated that most paths between arbitrary node pairs do not exist at a given time. Often nodes also just walk alone without communication opportunities. In order to deliver messages from a source node to the destination of a message, the store-carry-forward routing paradigm has been proposed, whereby the source or relay nodes may store the message and carry it until a better forwarding node is encountered. Here the perspective is to forward a message with several carry periods hop-by-hop to its destination node. Nevertheless, the path between the source node and the destination node have a long delay and may never exist.

Many flooding-based routing protocols have been proposed for opportunistic networking environments in order to improve the probability of the message delivery ratio. However, these protocols suffer from excessive resource consumption regarding storage, bandwidth, and energy. This excessive resource usage leads to a significant degradation of the routing performance, especially if we consider the fact that each node in the opportunistic network could be a mobile and battery-powered device with physically limited buffer size. With such buffer limitations of the mobile node, message drop events could occur due to buffer overflow especially with a high traffic pattern combined with an excessive flooding protocol. Forwarding strategies have to be identified to decide which messages should be selected for forwarding if the bandwidth is scarce and the transmission time limited. Also drop policies have to be identified that decide which messages to delete from the buffer once the buffer is full.

Besides the routing challenges, the neighbor discovery and link establishment process are noteworthy, as they also consume resources. The mechanism of neighbor discovery is needed especially when links are established using the infrastructure mode of the IEEE 802.11 Wi-Fi capabilities of the nodes. This connection option is currently the most available link option for smartphones and provides the highest possible bandwidth compared to other wireless communication options such as Bluetooth or NFC. Therefore, it is needed to investigate this step of neighbor discovery and link establishment with special consideration with regard to the signaling overhead and link establishment delay. It is desirable to reduce the control traffic required to build a stable and reliable link connectivity and thus to improve channel utilization and energy conservation. A further effect of improving the neighbor discovery is an impact on the performance of applied routing protocol in form of decreasing the transmission delay and increasing the message delivery ratio. To address the challenges of improving the performance of communications and routing protocols in opportunistic networks and to lower the message overhead and delay costs, this thesis focuses on the following main design objectives.

First, we design and evaluate a new beacon interval in the process of neighbor discovery and link establishment for infrastructure-based Wi-Fi communications. For that we investigate and analyze the traditional beacon interval and assess the performance of the neighbor discovery mechanisms. We propose to duplicate the traditional beacon interval for a better channel utilization and a higher energy efficiency. Various scenarios are used to evaluate the performance of the proposed Double Hundred Kilo Beacon Interval in terms of contact probability, delay and the channel utilization in comparison to the traditional beacon interval. The proposed

beacon interval results in an equal performance of the neighbor discovery mechanism while the signaling costs are halved and thus valuable energy conserved.

Second, we systematically and holistically evaluate all possible scheduling and dropping policies based on a single parameter of the message characteristics, namely arrival time, replication count, number of relayed nodes, time to live and message size. We systematically analyze the question of how the performance of the routing protocol in terms of delivery ratio, delay and message overhead is influenced if messages are selected for scheduling or dropping based on the message with the highest / lowest value with regard to a single of these parameters. We evaluated the impact of 121 scheduling and drop policy combinations using three scenarios with varying node speeds and bandwidths, as well as varying message sizes and generation intervals. Our exhaustive study shows that the impact of each specific message information in the scheduling and drop policies is highly depending on the network conditions. The specific message parameter which leads to the highest delivery ratio or lowest delay and overhead is different in each of the scenarios. The study is very useful to identify the interdependencies of the specific network conditions and the information relevant in the scheduling and drop policies.

Third, we use this insights to design and evaluate optimized scheduling and drop policies for flooding-based and utility-based routing protocols for opportunistic networks that lead to less message loss due to less buffer overflow and further increase the routing performance in terms of delivery ratio in comparison to prominent strategies in literature. Evaluation with several simulation setups shows that our proposed optimized scheduling and drop policies for the epidemic routing protocol and PRoPHET, an utility-based routing protocol, are either on par or better that comparable routing protocols while the traffic overhead and message delivery delays as significantly reduced.

In addition, we design and evaluate a replication-controlled multi-copy routing scheme, which especially aims to balance the need for message replication to improve the chances of the message to be delivered and the risk of congesting the network. This leads to a reduction of the message delivery probability. The proposed Replication Probability-based Routing Scheme explores the possibility of taking local node and message information into account to control the message replication and so increasing the delivery ratio and minimizing the overhead and delay of the messages. In our approach, the best carrier for a message is characterized by the message's delivery probability considering the replication count and hop count in a Markov chain model as well as the network status, information on the mobility of the node and its buffer information. We not only consider the mobility model statistics but also consider the user traffic and network conditions, such as congestion and buffer occupancy, especially when there is a contact with another node. The thesis shows that the node and the message information can serve as meaningful local information to achieve an appropriate message replication decision at each node. Therefore, the implemented routing scheme achieves high efficiency via an adaptive and precise routing design considering different network conditions.

In order to support these contributions, initially we created an overview on available evaluation environments for opportunistic networks and identified the tools that were used further on to evaluate the impact of our contributions. Within this thesis, we provide several contributions to increase the efficiency of opportunistic networks. For that we either increase the performance or decrease the costs for neighbor discovery, link establishment as well as delay-tolerant routing. Through this work, we hope to further support the spread of opportunistic networks.

Zusammenfassung

Opportunistische Netzwerke haben in den vergangenen Jahren einige Aufmerksamkeit der Forschungsgemeinschaft auf sich gezogen. Opportunistische Netzwerke zeichnen sich durch Knoten mit typischerweise drahtlosen Kommunikationsfähigkeiten aus, die sich typischerweise bewegen und entweder keine, ein oder mehrere Kommunikationspartner zur gleichen Zeit haben. Das Netzwerk gilt oft als so spärlich belegt, dass die meisten Pfade zwischen beliebigen Knotenpaaren zu einem gegebenen Zeitpunkt nicht existieren. Oft bewegen sich die Knoten auch nur alleine, ohne Kommunikationsmöglichkeiten. Um Nachrichten von einem Quellknoten an den Zielknoten zu übermitteln, wurde das Store-Carry-Forward-Paradigma vorgeschlagen, wobei die Quell- oder Weiterleitungsknoten die Nachricht speichern und transportieren können, bis ein besserer Weiterleitungsknoten angetroffen wird. Ziel dieses Ansatzes ist es, eine Nachricht mit mehreren Trageperioden, Knoten für Knoten an ihren Zielknoten weiterzuleiten. Oft umfasst der Multihop-Pfad zwischen dem Quellknoten und dem Zielknoten eine lange Verzögerung oder kommt letztlich doch nicht zustande.

Viele Flooding-basierte Routing-Protokolle wurden für Opportunistische Netzwerke vorgeschlagen, um die Wahrscheinlichkeit der Nachrichtenzustellung zu verbessern. Diese Protokolle leiden jedoch unter einem übermäßigen Ressourcenverbrauch bei dem Nachrichtenpuffer, der Bandbreite und der Energie. Diese übermäßige Ressourcennutzung führt zu einer signifikanten Verschlechterung der Routingperformance, da Nachrichten aufgrund voller Puffer in den mobilen Knoten übermäßig verworfen werden. Dies kommt insbesondere bei einem hohen Nachrichtenaufkommen kombiniert mit einem übermäßigen Flutungsprotokoll vor. Weiterleitungsstrategien müssen identifiziert werden, die entscheiden, welche Nachrichten für die Weiterleitung ausgewählt werden sollen, wenn die Bandbreite und Übertragungszeit knapp ist und eine Übertragung möglich ist. Es müssen auch Verwerfrichtlinien identifiziert werden, die entscheiden, welche Nachrichten aus einem vollen Puffer gelöscht werden sollen.

Neben den Herausforderungen des effizienten Routings sind auch die Schritte der Nachbarknotenentdeckung und der Prozess des Linkaufbaus hervorzuheben, da sie auch Ressourcen konsumieren. Der Mechanismus der Nachbarknotenerkennung ist besonders im Fokus, wenn Links durch den IEEE 802.11 Wi-Fi Infrastrukturmodus aufgebaut werden. Diese Verbindungsoption ist derzeit die am meisten verfügbare Link-Option für Smartphones, die wiederum die am weitesten verbreiteten mobilen Kommunikationsknoten sind. Darüber hinaus bietet Wi-Fi die größte Bandbreite im Vergleich zu anderen drahtlosen Kommunikationsoptionen wie Bluetooth oder NFC. Daher ist es notwendig, bei diesem Schritt der Nachbarknotenerkennung und des Linkaufbaus, den Signalisierungsoverhead und die Verzögerung beim Aufbau zu untersuchen. Es ist wünschenswert, den Signalisierungsverkehr zum Aufbau einer stabilen und zuverlässigen Verbindung zu reduzieren und somit die verfügbare Bandbreite im Link weiter zu erhöhen und den Energieverbrauch zu senken. Beschleunigt man den Linkaufbau, so verkürzt sich auch die Übertragungsverzögerung und die Nachrichtenzustellung im Routing verbessert sich. Um die Herausforderungen der Verbesserung von Kommunikations- und Routing-Protokolle in opportunistischen Netzwerken zu bewältigen und den Nachrichtenaufwand und -verzögerung zu senken, konzentriert sich diese Arbeit auf die folgenden Hauptentwurfsziele.

Zuerst entwerfen und bewerten wir ein neues Beacon-Intervall im Prozess der Nachbarknotenentdeckung und Linkeinrichtung für infrastrukturbasierte Wi-Fi-Kommunikation. Dafür untersuchen und analysieren wir das traditionelle Beacon-Intervall und beurteilen die Leistung der

Nachbarknotenentdeckungsmechanismen. Wir schlagen vor, das traditionelle Beacon-Intervall für eine bessere Kanalauslastung und eine höhere Energieeffizienz zu duplizieren. Verschiedene Szenarien werden verwendet, um die Leistung des vorgeschlagenen Double Hundred Kilo Beacon Intervalls in Bezug auf Kontaktwahrscheinlichkeit, Verzögerung und die Kanalauslastung im Vergleich zum herkömmlichen Beacon-Intervall zu bewerten. Das vorgeschlagene Beacon-Intervall erreicht die gleiche Leistung wie die vorangegangene Lösung, halbiert dabei aber die Signalisierungskosten und spart somit wertvolle Energie.

Zweitens evaluieren wir systematisch und ganzheitlich alle möglichen Weiterleitungs- und Verwerfrichtlinien, die auf einem einzigen Nachrichtenparameter basieren, nämlich Ankunftszeit, Replikationszahl, Anzahl der weitergeleiteten Knoten, Time-to-Live und Nachrichtengröße. Wir analysieren systematisch die Frage, wie die Performance des Routingprotokolls hinsichtlich Zustellwahrscheinlichkeit, Verzögerung und Nachrichtenoverhead beeinflusst wird, wenn Nachrichten zum Weiterleiten oder Verwerfen auf Basis des höchsten / niedrigsten Werts eines der Nachrichtenparameter ausgewählt werden. Wir haben die Auswirkungen von 121 Weiterleitungs- und Verwerfrichtlinien-Kombinationen anhand von drei Szenarien mit unterschiedlichen Knotengeschwindigkeiten und Bandbreiten sowie unterschiedlichen Nachrichtengrößen und Generierungsintervallen ausgewertet. Unsere ausführliche Studie zeigt, dass die Auswirkungen der einzelnen Nachrichtenparameter auf die Routingqualität in hohem Maße von den Netzwerkbedingungen abhängen. Der jeweilige Nachrichtenparameter, der zu der höchsten Zustellwahrscheinlichkeit oder der niedrigsten Verzögerung und dem niedrigsten Nachrichtenoverhead führt, in jedem der Szenarien unterschiedlich ist. Die Studie ist sehr nützlich, um die Abhängigkeiten der spezifischen Netzwerkbedingungen und der Nachrichtenparameter zu identifizieren, die in den Weiterleitungs- und Nachrichtenverwerfrichtlinien relevant sind.

Drittens nutzen wir diese Erkenntnisse, um optimierte Weiterleitungs- und Nachrichtenverwerfrichtlinien für floodingbasierte und utilitybasierte Routingprotokolle für opportunistische Netzwerke zu entwerfen und zu evaluieren. Die Evaluation mit mehreren Simulations-Setups zeigt, dass unsere optimierten Weiterleitungs- und Nachrichtenverwerfrichtlinien für das epidemische Routing-Protokoll und das utility-basiertes Routing-Protokoll PRoPHET entweder gleichauf oder besser sind als vergleichbare Routing-Protokolle, während die Verzögerung und der Nachrichtenoverhead deutlich reduziert werden. Darüber hinaus entwerfen und evaluieren wir ein replikationsgesteuertes Multi-Copy-Routing-Schema, das vor allem darauf abzielt, die Notwendigkeit einer Nachrichtenreplikation abzuwägen, um die Nachrichtzustellung zu verbessern und das Netzwerk nicht zu verstopfen. Unser Ansatz untersucht die Möglichkeit, lokale Knoten- und Nachrichteninformationen in der Nachrichtenreplikation zu berücksichtigen um so die Zustellwahrscheinlichkeit zu erhöhen und den Overhead und die Verzögerung der Nachrichten zu minimieren. Wir betrachten dazu nicht nur die Mobilitätsmodelle, sondern berücksichtigen auch Nachrichtenverkehrs- und Netzwerkbedingungen. Unsere Arbeit zeigt, dass Knoten- und Nachrichteninformation als sinnvolle lokale Information dienen können, um eine geeignete Nachrichtenreplikationsentscheidung in jedem Knoten treffen zu können.

Um diese Beiträge zu unterstützen, haben wir zunächst einen Überblick über verfügbare Evaluationsumgebungen für opportunistische Netzwerke erstellt und die Werkzeuge, die weiter zur Bewertung der Auswirkungen unserer Beiträge genutzt wurden, identifiziert. Im Rahmen dieser Arbeit bieten wir mehrere Beiträge zur Steigerung der Effizienz von opportunistischen Netzwerken. Dafür erhöhen wir entweder die Leistung oder senken die Kosten für die Nachbarknotenentdeckung, den Linkaufbau sowie für verzögerungstolerantes Routing. Durch unsere Arbeit hoffen wir, die Verbreitung opportunistischer Netzwerke weiter zu unterstützen.

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Contents

Chapter 1

Introduction

Communication networks, such as the Internet, enable participants to send each other messages and are an essential building block of today's economy and information-based society. The main current communication networks, such as the Internet or telephone networks, rely on a set of main assumptions that are given for wired networks and for wired networks with one final wireless link, such as in 802.11 Wi-Fi networks or in cell phone networking architectures. The first and very important assumption is the existence of an end-to-end path from a source to a destination. This assumption given, various routing protocols have been proposed and adopted to route a message from its source to its destination and thus defining the foundation of networking. Based on this principle, more and more complex protocols are defined which, eventually, offer a plethora of services in the networks we use daily.

Opportunistic networks [PPC06] are a subset of the communication networks, where the assumption of the existence of an end-to-end path from source to destination is not given. Opportunistic networks are characterized by wireless communication in local proximity, i.e. only close-by nodes can exchange messages, and further by intermittent connected networking. Through the limitation of the communication range of the nodes as well as their mobility, the network topology is highly dynamic and often isolated communication islands, i.e. isolated subgraphs, emerge. This is in contrast to other wireless, multi-hop networks, such as mobile ad hoc networks, which assume the connectedness of the network and thus the existence of end-to-end paths. Protocols implemented for mobile ad hoc networks, such as Dynamic Source Routing [JM01], Ad Hoc On Demand Vector Routing [IETF03] or Ant-based approaches [MGHS07, GMHS07, MGHS11] are therefore unable to address the routing challenges in opportunistic networks. The complete path discovery mechanism of these routing protocols may fail in opportunistic networks.

While within connected subgraphs in the opportunistic network routing is possible, i.e. multi-hop end-to-end paths exist, in general routing across the whole network is only possible using a store-carry-forward approach which introduces severe delay in the routing when no suitable communication partner is available. To cope with frequent, long time disconnections and to deal with variations in the link connectivity over time, i.e. different links most probably will be connected and disconnected due to node mobility, a node can store the message and wait until it has an existing link to a suitable next hop which also stores the message and waits for another stable link. The process of node discovery, link establishment and message forwarding is repeated until the message is delivered to its destination. This behavior, termed store, carry, and forward principle, has proven to be a viable way of routing in opportunistic networks.

Following the store-carry-forward approach, nodes must keep the messages and wait for the opportunity to forward the messages to the suitable relay node. This carrying phase introduces delays, which further arise due to topology dynamics in sparse networks, due to link conditions due to wireless propagation and node mobility. The buffering may take long periods of time until another node is encountered, messages are exchanged through specific protocols and the message continues its trip until delivery to its destination. As a result, nodes are often traveling alone or with the same set of neighbors, thus they are highly susceptible to many disruptions that causes the network to evolve to a set of disconnected regions of nodes. Therefore, the synchronous communication paradigm, i.e. protocols based on request / reply dialogues, perform poorly in opportunistic networks or even are impossible to implement.

In recent years, smartphones became a commodity and through the widespread and employment of wireless technologies for smartphones we face a situation, that a wide range of smartphones is constantly surrounding us. With the high density of smartphones around us, opportunistic networks could be run on these devices to interconnect different regions through wireless multi-hop links and to build attractive applications. The local wireless communication of the devices in opportunistic networks is often implemented through IEEE 802.11 connectivity and can be very fast in comparison to cellular mobile communication. Thus, applications which are aiming at local, high-speed, but delay-tolerant and disruption-tolerant communication can be well served with opportunistic networks. Examples for applications for opportunistic networks are chatting, local file-sharing, local file-synchronization or the aggregation of sensor data.

One essential characteristic of smartphone-based, i.e. Android-based, opportunistic networks is that in contrast to Ad Hoc Networking, nodes can only be active as hosts or clients of a local wireless connection. This detail is elaborated in [IG15, IG17]. Unrooted Android phones are only capable to connect to other Android phones using Wi-Fi Direct, Bluetooth or using the tethering function of the device. While the first two options are either unreliable or slow, the third option, tethering or "hotspotting", enables a node to create a Wi-Fi hotspot and other nodes to identify this hotspot and to connect to it. Once a message transmission is completed and no further messages are to be transferred, the node discontinue their link and become available for new connection partners. Thus, we consider pure 1-to-1 connections in opportunistic networks. So, nodes can find each other, connect to each other and initiate a higher level protocol for the exchange of messages. Based on this principle, opportunistic networks on plain, unrooted Android-based smartphones can be run and with Apps using the opportunistic networking functionality, interesting applications can be supported.

1.1 Problem Statement

The applications using the opportunistic network are mainly interested in three quality measures with regard to the opportunistic network.

- Delivery Ratio: This metric describes the number of received message in relation to the number of sent messages. Ideally all generated messages should be delivered, i.e. the ideal delivery ratio is 1. However, due to the missing end-to-end paths in opportunistic networks as well as the great uncertainty whether a path will be available over time, typically the delivery ratio is (much) lower than the optimum.

- Delay: This metric describes the average time a message takes from a source node to the destination node, in the case that the message arrives at it destination. A smaller delivery time, i.e. overall delay, is to be preferred as this would support a wider range of applications.

- Overhead: This metric describes the average number of message copies that exist in the network for a given message. As it is allowed to create copies, i.e. through the transmission of a given message to several neighboring nodes, typically the average copy count, i.e. the overhead, is raising above 1. More copies mean a higher probability of message delivery, but also at the same time consume valuable bandwidth as well as valuable storage space on the nodes.

The opportunistic networks, we consider, are motivated through connectivity options of Android-based smartphones, which are widely available nowadays. Due to the Wi-Fi options provided by plain Android, nodes can engage in 1-to-1 connections upon detection of each other based on the tethering / hotspot option available in Android. The nodes in the network follow the store-carry-forward approach, i.e. they carry messages around and might forward them to other nodes upon meeting other nodes. A node has to decide, once it connects to another node, which message to select for forwarding. Also, if a node receives new messages and its buffer gets full, it has to decide which message to drop from its buffer.

In order to optimize an opportunistic network for these three metrics, the various mechanisms that are active in the opportunistic network must be considered.

- First, the neighbor discovery and connection establishment can be optimized. When two nodes move in each other's communication range, they should detect each other and establish a wireless communication channel, if suitable, with the connectivity delay to be minimized.

- Second, once two nodes are connected, they have to inspect their messages in their buffers and decide which message to select for forwarding to the connected node. The message selection is done through scheduling mechanisms based on the information with regard to the specific message as well as further information about the network.

- Third, it is to be considered whether it is useful to forward the selected message to the connected node. It is not necessarily advantageous for the network, when messages are forwarded, as they consume valuable buffer space at the receiving node and might be transferred to nodes which have low chances to successfully deliver the message.

- Fourth, when messages are exchanged the situation might occur that the buffer of the receiving node becomes full and it is required to drop one or several messages. The buffer management strategies in use select the message to drop and thus have an implication on the potential success of a delivery. Those messages have to be selected for dropping which have the lowest probability for successful delivery.

- Fifth, when a message is forwarded and replicated in the network, a stopping rule needs to be considered when to stop the forwarding of the message to save resources or because the message delivery probability is low.

Goal of this dissertation is to optimize the various protocols and mechanisms that are active in an opportunistic network with regard to the three metrics, i.e. to increase the message delivery ratio, while reducing the message delivery delay and message overhead.

1.2 Contributions

We documented the achievements for this dissertation in six publications which follow the goal of optimizing the various elements in an opportunistic network. Namely, we first elaborated the simulation environment that allows us to propose new approaches in opportunistic networks and to evaluate the impact of them. Second, we focused on the connection establishment between two nodes aiming to quicken the process. And finally, we focused on routing by first evaluating the impact of message passing strategies and then proposing suitable routing protocols. We elaborate these points in the following short overview of contributions.

1.2.1 Survey on the Simulation Tools for P2P Networks, Mobile Ad Hoc Networks and Opportunistic Networks

In Chapter 2, we summarize the findings of our paper on simulation tools for p2p networks, mobile ad hoc networks and opportunistic networks, which we published in [CAS+16]. In this paper, we contribute an overview of simulation tools available for opportunistic networks. Only a few exist there, such as the Opportunistic Network Environment (ONE) [KKO10], DTN-Agent [VT10] and DTNSim2 [Wat06]. On the long term however, it seems reasonable to create a simulation environment for decentrally networked systems, including protocols for peer-to-peer networks, mobile ad hoc networks as well as opportunistic networks. The paper motivates, that PeerfactSim.KOM [Gra11] might be a good choice.

1.2.2 Neighbor Discovery and Connection Establishment

In Chapter 3, we summarize the findings of our paper [SG15] on the proposal and empirical analysis of an adapted beaconing in opportunistic infrastructure communication using Wi-Fi technology. In [SG15], we analyze communications and control traffic exchanged between the master device and its station at the MAC layer with the aim for understanding and improving the connection establishment between the master device and the station nodes within a Wi-Fi connection. Precisely this part considers the broadcasting of beacon frames which are sent by the master device to discover neighbors (one hop stations) at fixed intervals. The contribution of this research is to propose and evaluate a Double Hundred Kilo Beacon Interval (2HKBI) for opportunistic network infrastructure communications. Where the traditional beacon interval of 100 time units is a target for low-latency and high traffic Wi-Fi applications. This traditional beacon interval is used by different Wi-Fi vendors and less suitable for opportunistic network communications. The opportunistic networking stations have limited resources in terms of storage and energy and assume delay-tolerant applications. Our experiments show that the proposed 2HKBI beacon interval provides a significant reduction of the energy consumption and maximizes the channel utilization compared to the commonly used beacon interval.

1.2.3 Scheduling and Buffer Management for an Optimized Message Selection

In Chapter 4 we summarize our findings from our publication in [SPG16a] on the buffer management of nodes in opportunistic networks. Routing and buffer decisions at intermediate relay nodes take impact on the performance of the network. The buffer management strategies decide on which messages will be processed while being able to forward messages to other nodes. Also it decides which messages to drop from the buffer, once the buffer is full. The buffer management consists of policies which complement with scheduling of the routing protocol such as in an epidemic routing protocol. The main challenge is how to make a trade-off between replication and dropping to ensure achieving of the desired performance as in epidemic control spreading, with threshold control on the spreading of the message we achieve the desired delivery ratio with minimum overhead and energy consumption.

We study the scheduling and dropping policies developed for the epidemic routing protocol in Chapter 4. We also conducted a performance comparison among selected well-known scheduling and drop policies. Simulations with 121 scheduling and buffer management combinations display the performance of epidemic routing with regard to delivery ratio, average delay and overhead ratio. The results show, that there is not one single golden rule for the scheduling and buffer management strategy, but rather that each scenario might require a specific selection of the buffer management strategies for an optimal routing performance.

1.2.4 Optimized Buffer Management for the Routing Protocol PRoPHET

In Chapter 5, we summarize our findings from our publication in [SPG16b]. We propose a new message scheduling and dropping framework (DFP-DDP) for an utility-based routing protocol (PRoPHET) based on our observations in [SPG16a]. PRoPHET [GDLD11] is one of the most popular routing protocols for opportunistic networks and the basis for our adapted buffer management strategies. We developed the buffer management policy based on the mechanism of the forward error approximation and dynamic drop policy. The decision of forwarding is made when there is a sufficient difference in the delivery predictability values between encountered nodes. The dropping decision for the buffered messages is made based on the utility function which considers message information such as hop and replication counters, in addition to the time to live (TTL) and buffer times. The simulation results show that the performance of the PRoPHET routing protocol is improved by our proposed buffer management policies by increasing the average delivery ratio while decreasing the overhead.

1.2.5 A Replication Control Scheme to Balance the Spread of Messages

In Chapter 6, we summarize the findings of our publication in [SIG16]. We formulate an optimization problem of multi-copy distributed routing based on the number of the messages in the system as well as buffer information of relaying nodes. We implement the problem with three different objectives: minimum number of replications, minimum number of hops,

and maximum number of delivered messages. We solve the problem using parameters from simulated networks. Output results are used as a performance benchmark to compare with the heuristic (non-optimal) protocols. We show in simulations, that by limiting the replication count of messages in the network, the message delivery increases as the scarce transmission capacity is used for more messages that would otherwise be replicated less.

1.2.6 A Routing Scheme based on the Delivery Probability in Routing

In Chapter 7, we summarize the findings of our publication in [SIG17]. There we study distributed non-optimal routing protocols developed for opportunistic networks and conduct a performance comparison among selected well-known protocols (Epidemic [VB+00b], Spray & Wait [SP05]) representing the different types of routing protocols, namely limited and full flooding. Based on these comparisons, we draw conclusions and present guidelines to design an efficient opportunistic routing scheme.

Given the protocol design guidelines in Chapter 7, we develop our opportunistic routing scheme, which combines the strengths of two of the available routing protocols (Epidemic [VB+00b], Spray & Wait [SP05]) to provide a better delivery ratio with lower network overhead. The protocol utilizes a stopping rule optimization to estimate the message delivery probability to the destination while minimizing the number of message copies throughout the network. Our heuristic distributed scheme, presented in Chapter 7, uses probability replication control among network nodes to exclude nodes that are not expected to significantly increase the probability of delivering the message to its destination. Simulation results show that our scheme achieves lower network overhead while achieving the same or better delivery ratio compared to the other routing protocols.

1.3 Thesis Organization

This thesis is organized as the following sequence. Chapter 1 presents an introduction for opportunistic networks and its routing challenges and models. It lists the contributions and research questions that are discussed through this dissertation. Chapters 2 -7 provide summaries for the published papers of the author. Chapter 2 introduces a survey [CAS+16] for different simulator tools for peer-to-peer, mobile ad hoc and opportunistic networks. Chapter 3 presents a summary of [SG15] which suggest a new beacon interval for device to device Wi-Fi communications in opportunistic networks. Chapter 4 includes a summary of [SPG16a] which displays an analysis of the performance of epidemic routing using 121 different scheduling and drop policy combinations. Chapter 5 introduces a summary of [SPG16b], a paper in which we improve PRoPHET's routing performance by implementing adapted scheduling and dropping policies as buffer management. Chapter 6 presents a summary of [SIG16] in which we propose and evaluate a routing framework which targets to control epidemic greedy replication. Chapter 7 presents a summary of [SIG17] which proposes and evaluates a new opportunistic routing protocol. Finally, Chapter 8 summarizes the thesis conclusion, and suggests interesting and challenging research directions for future work.

Chapter 2

The State of Simulation Tools for P2P Networks on Mobile Ad-Hoc and Opportunistic Networks

This chapter summarizes the contributions and gives a verbatim copy of our paper [CAS+16]:

> Ahmad Cheraghi, Tobias Amft, Salem Sati, Philipp Hagemeister, Kalman Graffi: *The State of Simulation Tools for P2P Networks on Mobile Ad-Hoc and Opportunistic Networks*. Accepted at the 10th IEEE 6th International Workshop on Context-aware Performance Engineering for the Internet of Things (ContextQoS), In Proceedings of the 25th IEEE International Conference on Computer Communication and Networks (ICCCN), Waikoloa, Hawaii, USA, August 2016.

This paper [CAS+16] presents a survey for the current status of simulations tools used in a peer-to-peer (P2P), opportunistic networks (OppNet), and mobile ad hoc networks (MANET). The paper targets to find a suitable evaluation tool that can simulate p2p overlays on opportunistic and/or mobile ad hoc networks. Based on the requirements of three network environments, we list the various simulation tools which were proposed for each one of the three networks. Those simulation tools are analyzed concerning criteria such as availability, timing and event concept, scalability of the simulation, implemented protocols, validated models and the support for multiple layers. The simulators are selected based on their popularity in literature.

The main aim of this paper is to identify which simulator is the most suitable simulator for running p2p, opportunistic and mobile ad hoc networks at the same time. The selected simulator should support the functionality of different layers where the p2p and opportunistic networks are considered being application networks over the movement and connectivity network such as mobile ad hoc networks. The different movement models are considered as underlay layers which consist of different movement patterns such as Random Way Point and Random Walk. While several simulators are available for each network type of the tree different networks, none of these available simulators, each for a specific network type designed, can support a combination of all three network types at once.

The paper proposes besides the survey also a guideline for a suitable simulator which combines these different three network types. The paper points that only some of the simulators can fulfill the requirements, which are necessary for setting up a simulation environment for p2p,

opportunistic and mobile ad hoc networks. As examples, the paper considers PeerfactSim.KOM [Gra11, KKH+06, KKM+07, FG13] and OverSim [BHK09] as common p2p simulators to simulate different types of p2p networks. The survey considers the ONE simulator [KKO10], DTN-Agent [VT10] and DTNSim2 [Wat06] as the most common simulators which can be used to simulate opportunistic network environments. For mobile ad hoc networks the paper takes OMNET [VH08], ns-2 [UC 93] and ns-3 [nP06] as common MANET simulators. But actually, none of the current simulators supports these three kind of networks at once.

The paper gives an in-depth analysis and discussion for the most suitable simulators for these combined different network categories. The analysis identifies the function of the different layers required in such a simulator, ranging from the upper most layer as application layer to the lowest layers of the underlay which consist of the routing layer and movement layer. This paper introduces use cases for such combined networks, such as a scenario of user-hosted files or services sharing, explicitly without the option of accessing the Internet. The second use case considers as bandwidth-demanding applications, such as interest-based wireless file-sharing, which is quicker served through local Wi-Fi-communication.

From the authors point of view, the PeerfactSim.KOM simulator [Gra11, KKH+06, KKM+07, FG13] seems most suitable for the integration of these combined networks. The authors believe that the PeerfactSim.KOM simulator's main benefit is the support of various network layers from its origins. P2P network elements such as overlays, data management mechanisms, monitoring overlays, and sophisticated applications are already supported by the simulator.

Also PeerfactSim.KOM comes with a mobility layer that might become the basis for MANETs. The remaining to be done for simulating the multiple networks, is the implementation of an opportunistic layer with suitable protocols. As another suggestion, the paper considers ns-3 [nP06] as well to simulate these three networks together. Ns-3 is missing the implementation of p2p protocols and the OppNet layer with suitable protocols.

This overview of simulators for various networks is related to the methodology of this dissertation. It is essential to identify in advance suitable evaluation tools, as throughout our research the simulation of various protocols for opportunistic networks is the common approach the evaluation. For purely opportunistic networks, the ONE simulator [KKO10] seems most suitable. We used it to evaluate all further research contributions.

The reviewing and selection process of the IEEE International Conference on Computer Communication and Networks (IEEE ICCCN) 2016 resulted in an acceptance rate of 30%. Ahmad Cheraghi organized the paper and collected and analyzed the data related to MANET simulators. Tobias Amft collected and summarized the information related to p2p simulators. Salem Sati, the author of this dissertation, collected and summarized the relevant information related to OppNet simulators. Philipp Hagemeister contributed the use cases in the paper, and finally, Kalman Graffi contributed to the introduction and the methodology of this paper.

Chapter 3

Adapting the Beacon Interval for Opportunistic Network Communications

This chapter summarizes the contributions and gives a verbatim copy of our paper [SG15]:

> Salem Sati and Kalman Graffi: *Adapting the Beacon Interval for Opportunistic Network Communications.* In Proceedings of International Conference on Advances in Computing, Communications and Informatics (ICACCI), 10-13 August 2015, Kerala, India.

This paper aims to improve the connection establishment between the Wi-Fi base station and client in infrastructure-based opportunistic communications. The paper investigates the impact of the timing of the beaconing with respect to the IEEE 802.11 standard for the application use case of an opportunistic network. The authors suggest to adapt the interval of the broadcasting beacon which is sent by the master device to discover neighbors, i.e. stations. The traditional beacon interval is 100 time units (TU) proposed by most Wi-Fi product vendors nowadays. This 100 TU is targeted for low-latency Wi-Fi applications and less suitable for opportunistic networking. The opportunistic networking stations have limited resources and assume delay tolerant applications. In the paper, we propose an empirical analysis of the functionality of the beacon interval and introduce the *double hundred kilo beacon interval* (2HKBI) approach.

For the background, we reviewed studies of previous research related to adapting the beacon interval. We identify the metrics and tools which are used to gather the data from the experiment scenarios and investigate the results of the experiment scenarios of comparing the proposed 2HKBI beacon interval with traditional 100 TU beacon.

The main question of the paper is how to improve the link utilization and how to reduce the power consumption by reducing the control traffic of connection establishment. This question is related to the dissertation's aim of resource conservation in opportunistic networking environments. This challenge of resource conservation aims to reduce the traffic control flow which impacts immediately the data flow. This improvement minimizes the storage delay and transmission cost, finally the improvement also reflects on the power or energy consumption of opportunistic mobile nodes.

As contribution in this paper we propose and evaluate a new double hundred kilo beacon interval for the opportunistic communication which considers energy-efficiency of the neighbor

discovery using Wi-Fi technology of the infrastructure mode. This paper suggests to increase the beacon interval of the commercial Wi-Fi appliances to minimize the power consumption of the WNIC of the station and to improve the channel utilization between the master device and the station. The traditional default value of a fixed beacon interval is equal to 100 TU which is equal to 102.4 milliseconds. This value of 100 TU is defined for WLANs as a trade-off between the device's requirements on mobility, power saving, in addition to contact probability, and the application requirement of sensitive to latency application and real-time support which impact the end-to-end delay.

The proposed approach is compared to the traditional beacon interval which is the target for low-latency Wi-Fi applications and less suitable for opportunistic communications application where the delay-tolerant application is considered less sensitive to delay compared to latency-critical applications or MANETs as application. In most of current commercial master Wi-Fi devices supporting 802.11 b and/ or g, the beacon interval by default has a fixed value of 102.4 millisecond which is considered as 100 TU. Moreover, most vendors and Wi-Fi appliance manufactures make this interval configurable as advanced wireless setting. This feature enables the administrator and users to modify the fixed beacon interval as positive integer multiple of kilo-microseconds (1024 μs). This integer can be ranged from 20 to 1000 times and is defined in the vendor's or appliance firmware's settings. The administrator or user can configure this beacon interval to a any value other than the default fixed value of 100 TU. In this paper, we also analyze the impact of modifying the default beaconing interval by increasing or decreasing the value of the beacon interval with regard to the default value of 100 TU. This analysis is required to answer the question of why the default interval is chosen as 100 TU or 102.4 milliseconds.

The methodology of the paper is based on that the efficiency and performance of the proposed 2HKBI approach for opportunistic communications is evaluated using a series of empirical experiments. The experiments investigate the impact of the beacon timing with respect to the IEEE 802.11 standard for the application uses case of an opportunistic environment. In order to evaluate the performance of the proposed 2HKBI approach in comparison with the 100 TU beacon interval, in the paper we employ the Linux platform on both master and station devices and adapt the beacon interval. The authors consider the mobile opportunistic scenario in which a neighboring node is detected and a connection is established with one station node and a single master device. Every experiment uses a monitor node to capture MAC frames for analyzing the results of each scenario. To compare the performance of the two considered beacon intervals 2HKBI and the traditional 100 TU, the experiments measure a set of metrics such as delay and bandwidth in addition to the consumed power. All measurements are done by real Linux tools and applications.

The measurements in the paper show that the efficient usage of energy and bandwidth in opportunistic communications is significantly improved by applying the proposed 2HKBI based on duplicating the traditional beacon interval. The performance of the proposed 2HKBI is evaluated by an empirical scenario in a simple test-bed. Using a single master device and a single station, the obtained results of this simple test-bed show that the proposed 2HKBI can provide a significant energy conserving and overhead reduction with respect to the traditional beacon interval of 100 TU. The proposed 2HKBI reduces the overhead by up to 51 % with the same miss contact probability of the traditional 100 TU beacon interval. Moreover, the 2HKBI approach improves the energy-efficiency of around 35 % with respect to traditional 100 TU in infrastructure-based opportunistic device-to-device communications.

The International Conference on Advances in Computing, Communications and Informatics (ICACCI) 2015 received a record number of 2915 submissions in the year 2015 with 1712 manuscripts for the main conference, out of which 404 (365 regular papers and 39 poster papers) have been accepted (24%). Salem Sati considered the conception and design of the paper, also he performed the data collection, analysis and interpretation of the experiments, the writing and drafting of the paper was also done by Salem Sati. Kalman Graffi was involved in the discussion regarding the measurement methodology and did the critical revision and final approval of the paper.

Chapter 4

Analysis of Buffer Management Policies for Opportunistic Networks

This chapter summarizes the contributions and gives a verbatim copy of our paper [SPG16a]:

> Salem Sati, Christopher Probst, Kalman Graffi: *Analysis of Buffer Management Policies for Opportunistic Networks*. Accepted at the International Workshop on Context-aware Performance Engineering for the Internet of Things (ContextQoS), collocated with ICCCN 2016, In Proceedings of the 25th IEEE International Conference on Computer Communication and Networks (ICCCN), Waikoloa, Hawaii, USA, August 2016.

This paper presents a comprehensive study investigating the impact of the various message parameters, such as the arrival time, replication count, number of relayed nodes, time to live and message size, in the buffer management decisions for both scheduling and dropping on the performance of epidemic routing in an opportunistic network. The buffer management decision consists of the queue sorting, which determines the order of stored messages in the node's buffer. Following for example the arrival time as main criteria, that message with the minimum or maximum arrival time would be selected for processing. The drop decision on the other hand determines the message to be selected for dropping, if congestion occur.

This paper provides a comprehensive study of different scheduling and drop policies, which are commonly used as buffer management rules in an opportunistic environment and compares those different policies with each other based on four metrics namely delivery ratio, overhead metric, delivery delay as well as a composite metric. The composite metric combines the other three metrics through a simple weighted average calculation. In total 121 scheduling and dropping strategy combinations are considered.

The simulation study is performed using the ONE simulator [KKO10]. The simulation setup, scenarios and evaluation aims are chosen and discussed based on the modeling of the opportunistic network considering three scenarios with nodes of various speed and capacity as well as a workload of different capacity. Evaluation shows, that there is not one single scheduling and drop configuration that performs overall well in all three scenarios. The scheduling and drop policies behave quite differently in the various simulation scenarios which represent various use cases. This paper elaborates the impact of the various parameters on the performance of the epidemic routing protocol and thus provides with this study a basic help for future dy-

namic buffer management approaches. The paper helps routing protocol researchers to select a suitable buffer management policy based on the dynamics given by the expected network characteristics.

The main goal of this paper is to answer the question of what is the impact of various message parameters, namely arrival time, replication count, number of relayed nodes, time to live and message size, on the buffer management decisions and what is the impact of different buffer scheduling and drop decisions on the performance of the epidemic routing protocol. These questions are related to the dissertation's main question of resource conservation issues in opportunistic networks. In addition, these two questions clarify how to implement the replication control strategy and congestion control of routing protocols for opportunistic networks. The buffer management takes impact on the performance of opportunistic routing protocols. This impact comes from the fact that all opportunistic routing protocols are following the store-carry-forward and especially in Android-based opportunistic networks, mainly the communication partners are connected exclusively. Thus, messages are passed one after another and he buffer management policies take impact on the routing performance and energy efficiency.

In this study, an effective buffer management is analyzed and investigated based on epidemic routing performance in terms of message delivery probability and delay. In addition, the message overhead is considered as resource consumption metric. We evaluated the traffic load for three different scenarios which mean different congestion criteria. Furthermore, the paper proposed composite metric which is normalized and an equally-weighted average of the delivery ratio, overhead and delay metrics, this composite metric expressed as a percentage value.

We tested 121 different configuration policies with both scheduling and drop policies of the buffer management combined. For each of the two processes, scheduling and drop decisions, we have 11 strategies which in total give $11 \cdot 11$ combinations. The 11 strategies are first random and then the two options of minimizing as well as maximizing the 5 message parameters arrival time, replication count, number of relayed nodes, time to live and message size. For the buffer management policy usually only these local parameters are considered as criteria as they are typically carried by the message and can be measured by the node.

Based on the routing protocol, the scheduling policy may be overridden. Often, the routing protocol replicates a message from the head of the node's buffer queue (minimum arrival time) and decides, which nearby node is best suited for forwarding this message towards to the destination. But it can also decide to ignore the scheduling policy completely and choose a message by itself as applied by some routing protocols such as PRoPHET routing protocol, which is a quite successfull routing protocol. While the impact of the scheduling policy completely depends on the routing protocol's metric or weight, the drop policy directly affects the routing protocol's performance, if congestion occurs. Some routing protocols, such as the Epidemic routing protocol, even encourage excessive bandwidth usage by replicating the same message multiple times to achieve a hih delivery ratio. By actively defining for the epidemic routing protocol which scheduling and drop policy to use, we can investigate the various performances under three scenarios.

The methodology of the paper was based on the simulation-based evaluation of epidemic routing with 121 different buffer policies of scheduling and drop decisions for the various message parameters, namely minimizing or maximizing the arrival time, replication count, number of

relayed nodes, time to live and message size. The evaluation in the paper includes three scenarios and a composite scenario. Each simulation reports the measurements for each evaluation metric, namely the delivery ratio, the delay of delivered messages, the message overhead as well as a composite metric, where the composite metric is the average of the respective metrics of the previous three scenarios. While the composite metric is quite arbitrary, it still is useful to identify scheduling and drop strategies that are performing quite well with regard to all scenarios and all metrics.

In conclusion, the simulation evaluation shows that the strengths and weaknesses of different buffer management policies and points that there is not one policy based on single message information decision. In the first scenario, which generates only moderate traffic, the highest delivery ratio is reached using the message with the minimum hop-count as scheduling policy and the message with the minimum time-to-live as drop policy. The second scenario modifies the first scenario, by decreasing the size of the moderate traffic and adding frequent traffic using small messages. Regarding the delivery ratio, the best combination uses minimum replications and maximum hop-count as scheduling and drop policy respectively. The third scenario extends the second scenario, by adding demanding traffic using large but rarely sent messages. The highest delivery ratio is reached using messages with maximum time-to-live and maximum message size as criteria for the scheduling and drop policy, respectively. Looking only at the scheduling policy, the best strategy is once to select messages with a minimum hop-count, minimum replications as well as a maximum time-to-live. For the drop policy, the best performing policies in the three scenarios are minimum time-to-live, maximum hop-count as well as maximum message size. Taking a policy that performed best in a previous scenario might seemingly perform quite bad in another scenario. This shows the broad range of the impact of scheduling and drop policies.

This paper helps to design dynamic buffer management strategies through an in-depth analysis of the impact of buffer management strategies on epidemic routing in terms of different metrics such as a delivery ratio, overhead and latency. As the study shows, the routing performance is also inherently influenced by the choice of the buffer management rules. In the following papers we further investigated how to improve the routing in opportunistic networks beyond optimized buffer management rules.

The reviewing and selection process of IEEE International Conference on Computer Communication and Networks (ICCCN) 2016 resulted in an acceptance rate of 30%. Salem Sati suggested the paper study conception and design, the selection of metrics as well as the interpretation of the data. Christopher Probst implemented the policies, acquired the data and drafted the paper. Kalman Graffi contributed to the methodology and provided a critical revision of the paper. Please note that subsequent to the verbatim copy of the paper, we give a short appendix with increased tables for better readability.

Chapter 5

Implementing Forward and Drop Policies for Improving PRoPHET's Routing Performance

This chapter summarizes the contributions and gives a verbatim copy of our paper [SPG16b]:

> Salem Sati, Christopher Probst, Kalman Graffi: *Implementing Forward and Drop Policies for Improving PRoPHET's Routing Performance.* In Proceedings of the 12th IEEE International Conference on Mobile Ad-hoc and Sensor Networks (MSN 2016), December 16-18, 2016, Hefei, China.

This paper elaborates on PRoPHET [GDLD11], which is a common routing protocol for opportunistic networks. PRoPHET determines based on previous contact information a delivery probability per node, which can be compared and thus allows to decide whether a message should be forwarded or not. It was updated from contact events as in version 1 to contact duration as in version 2, but it still needs to improve its performance compared with other routing protocol such as MaxProp [BGJL06]. In this paper, we propose a stopping rule as forward strategy for the PRoPHET routing protocol, where this forward strategy criteria depends on the difference of the probability values between the encountered nodes. Furthermore, this forward strategy is combined with a dynamic drop policy to improve the performance of the PRoPHET routing protocol. Thus, we directly apply the observations from our contributions in Chapter 4 to PRoPHET. This paper optimizes the routing performance of PRoPHET based on reducing the number of relayed messages while keeping a desired delivery ratio.

To improve the resource conservation, we propose new rules for message forwarding when encountering nodes. A forwarding error approximation is used to give the optimal threshold of the forwarding decision. In addition, in this paper we propose a dynamic drop policy which considers delay and overhead of the message based on multiple parameters. The main goal of this paper is to answer of how to implement effective forward and drop policies as buffer management to improve the performance of PRoPHET version 2 routing protocol [GDLD11]. This question is related to the dissertation's main question of resource conservation issues in opportunistic networking environments on the one hand, and on the other hand, the dissertation considers the question of how to implement buffer management for improving the performance of both flooding and utility-based routing protocols. Our paper [SPG16b] contributes an analytic study and proposes a forward policy for PRoPHET routing termed Difference Forward

Predictability (DFP), which is calculated based on the forward error approximation as forwarding decision. This Difference Forward Predictability is a new forward strategy which considers the difference between the delivery probability of an encountered node towards the destination of the selected message. In addition, the DFP strategy takes the forward error approximation as forwarding decision for minimizing the overhead which impacts on the resource conservation of the nodes. On the other hand the paper proposes the Dynamic Drop Policy (DDP), which considers the delivery probability of the message, the buffering time at the relay node and the overhead by the single message. The proposed Dynamic Drop Policy is designed to use the message information, this information approximates the number of message copies spread in the network. This information helps to identify when the message will be dropped and which message to select to drop.

Thus, the paper proposes the DFP-DDP framework for buffer management for PRoPHET based on a mathematical analysis of PRoPHET version 2. We implemented the framework and evaluate it using the ONE simulator [KKO10]. The default strategy proposed by the PRoPHET Internet-Draft, GTRT, forwards the message if the delivery probability to the destination of the message for the encountered node is higher than the node taking the decision. The Internet-Draft proposes many other strategies, such as GTRTMax which applies ordered GTRT taking into account the delivery probability of encountered node towards the message destination. The evaluation compares the proposed DFP-DDP framework as buffer management with GTRTMax as forward strategy with three different representative drop policies which are First-In-First-Out (FIFO, minimum arrival time), Evict-Shortest-Lifetime-First (SHLI, minimum life time) and Evict Most Forwarded First (MOFO, maximum replication counter). In addition, we consider Maximize Replication (MaxRep) and Maximize Hop Count (MaxHop) as message-related parameters to decide which message to drop. We compare the performance and costs of these drop policies in combination with PRoPHET version 2 with GTRTMax as forward strategy.

As the TTL and the workload have a very large influence on the quality and costs of the routing protocol, we varied the TTL between 5 values, namely 100, 200, 300, 400 and 500 minutes. Also we varied the workload to match different traffic patterns. To reflect different traffic situations, we consider 3 scenarios. Scenario 1 only considers 80 pedestrians with a buffer size of 5MB, a message creation interval of 25s to 35s and message sizes ranging from 500KB to 1 MB. In Scenario 2, in addition to those 80 pedestrians from Scenario 1 also 40 cars join in. The scenario reflects a information-centric use case in which small (64KB - 512KB and 512B - 2KB) messages are quickly exchanged. Here the cars have a message creation interval of 1s - 5s. Finally, in Scenario 3 we investigate the effects of larger files and even faster nodes. 80 Pedestrians generate 1MB - 5MB large messages every 60s to 120s. 40 cars generate at an interval of 25s to 35s messages of 64KB to 512KB, while 6 nodes in trains generate every 1s to 5s messages of size 512B to 2KB. Through the variety of scenarios, in combination with the 5 values for the TTL we are able to fully reflect the quality of the proposed DFP-DDP policies in comparison to the other forward and drop policies.

The delivery ratio is the success indicator of the routing protocol's performance. Evaluation shows that only the proposed DFP-DDP, SHLI and MOFO achieve good results in terms of delivery ratio. The overhead ratio for varying the TTL of the messages and the traffic rate through the scenarios is the main metric regarding the resource consumption. Here it is worthwhile to mention that the proposed DFP-DDP has the lowest traffic overhead compared with the other different drop policies. The overhead ratio of the proposed DFP-DDP stays with

few exceptions always at a very constant level lower than all compared different drop policies. A decision on the quality of the remaining drop policies is given through the observation of the delay of the delivered messages. The proposed DFP-DDP considers both the TTL as well as the buffer time and thus gains an additional advantage. The MOFO policy does not consider the delay at all, as it uses the message overhead. MaxHop and MaxRep ignore the delay completely. The evaluation results show that the proposed DFP-DDP policies improve the performance of PRoPHET in terms of message delivery ratio, overhead, and delay.

Thus, in this paper we propose the new buffer management policies DFP-DDP for PRoPHET and evaluated its performance. The performance of the proposed DFP-DDP policies is analyzed with different message TTLs and different traffic scenarios. The proposed DFP-DDP framework is better that the existing approaches, namely GTRTMax scheduling with different drop policies such as FIFO, MOFO, SHLI, MaxRep and MaxHop, as it is able to minimize the overhead ratio and the delay while being best in the message delivery.

The idea of the proposed buffer management framework is based on that it uses the forward error probability as forwarding decision and a dynamic drop policy which is considering the overhead and delay. Therefore, the framework improves the performance of PRoPHET protocol version 2 in comparison to PRoPHET's standard buffer management and also some further promising combinations.

The contributions of Salem Sati were the provision of the idea an mathematical analysis of the paper, the conduction of the experiments and analysis of the results as well as the drafting of the paper. The implementation was done by Christopher Probst, and the paper revision was done by Kalman Graffi.

Chapter 6

Dynamic Replication Control Strategy for Opportunistic Networks

This chapter summarizes the contributions and gives a verbatim copy of our paper [SIG16]:

> Salem Sati, Andre Ippisch, Kalman Graffi. *Dynamic Replication Control Strategy for Opportunistic Networks.* Accepted at the 3rd National Workshop for REU Research in Networking and Systems. In Proceedings of the 6th International Conference on Computing, Networking and Communications (ICNC), Silicon Valley, USA, January 26-29, 2017.

This paper addresses the issue of epidemic replication control, i.e. the question on when an epidemic message flood should be stopped as the probability of delivery is not increasing but rather the scarce bandwidth for the transmissions could be used more valuabaly for other messages. We formulate this problem as a controlled finite discrete Markov chain and derive the optimal closed-loop control for the replication policy. For this, we propose a model for opportunistic networks based on an ordinary differential equation approximation, by considering the performance of the epidemic replication control policy over finite networks. Numerical results show that this dynamic replication policy performs close to the optimal closed-loop policy. The main goal of this paper is to answer, of what is the fair point which makes a suitable trade-off between delivery delay/ratio and resource consumption in an opportunistic network based on the epidemic modeling of Markov chains. This question is related to the thesis's main question of resource conservation issues in an opportunistic networking environment.

The paper's approach and contribution is, first, our analytic study and second a proposed replication policy for Epidemic routing termed *Most Of Storage and Transmission – with Replication Probability Threshold* (MOST-RPT) which integrates an optimal delivery probability policy as a function of the message hop-count combined with a replication counter and a rule for the optimal number of message copies in the network. This replication policy for epidemic routing protocol integrates an optimal delivery probability policy as stopping rule for the optimal number of message copies in the network. The optimality of MOST-RPT is based on the assumption that inter-contact times are distributed exponentially. Furthermore, the paper assumes that nodes move independently as independent and identically distributed random variables as well as that each node knows the average inter-contact rate in the network. Based on this, the proposed MOST-RPT provides a comprehensive policy which combines the direct delivery probability as replication counter and the global delivery probability from source to

destination. MOST-RPT is a dynamic function of two important states which are hop-count as storage metric and replication counter as transmission metric. The inter-contact time is considered as node mobility pattern in addition to the message time-to-live (TTL). These parameters make MOST-RPT an efficient replication policy framework regardless of the nodes' density in the network. The main objective for the MOST-RPT policy is to maintain a maximum resource consumption in form of a maximum number of replications per single message as message copy criteria.

We implemented our analytic model for the stopping policy based on the Markov chain in the ONE simulator [KKO10]. We evaluate the performance of MOST-RPT in comparison with five different dropping policies for the epidemic routing algorithm which are First-In-First-Out (FIFO, minimum arrival time), Evict-Shortest-Lifetime-First (SHLI, maximum time-to-live), Evict Most Forwarded First (MOFO, maximum replication counter) as well as Maximize Replication (MaxRep) and Maximize Hop Count (MaxHop) as message-related parameters to decide which message to drop. We evaluate these six drop policies with the epidemic routing protocol with different message TTL and different traffic load patterns and compare the performance with regard to the message delivery ratio, the delivery delay as well as the message overhead. The epidemic routing protocol use the FIFO replication strategy as scheduling policy, i.e. as strategy to decide which message to forward next.

In the evaluation we consider three scenarios with different traffic situations. Scenario 1 only uses 80 pedestrians with a buffer size of 5MB per node, the traffic load has a message creation interval of 25s to 35s, in addition the message size ranges from 500KB to 1 MB. Scenario 2 has in addition to those 80 pedestrians of Scenario 1 further 40 cars joining in the simulation area with small (64KB - 512KB and 512B - 2KB) messages which are quickly exchanged. In this scenario the cars have a message creation interval ranged from one message per 1s - 5s. Finally Scenario 3 investigates the effects of larger files and even speedy nodes. 80 Pedestrians generate 1MB - 5MB large messages with a message generation interval of one message per 60s to 120s. 40 cars generate at messages of the size 64KB to 512KB every 25s to 35s messages. 6 further nodes are consider as being on trains, generating a message of size 512B to 2KB every 1s to 5s.

The simulation results show that MOST-RPT gives help to design new forwarding schemes for utility-based routing protocols to achieve better performance. MOST-RPT outperforms all other policies except MOFO with regard to the delivery ratio in all scenarios. MOFO's performance is only in one scenario slightly better. In terms of delay, MOST-RPT outperforms all other policies by far. And also with regard to the message overhead, MOST-RPT is the second best in all scenarios. While Max-Rep is most resource conserving, it is worst in the delivery ratio and delay. On the other hand, while MOFO is outperforming MOST-RPT in one scenario, it is second-worst behaving in terms of overhead. Thus, MOST-RPT provides an ideal trade-off with being nearly in all cases best in terms of delivery ratio in combination with being best with regard to the delivery delay as well as second-best with regard to the message overhead. This is due to that the proposed MOST-RPT forwarding and dropping policy is constructed based on an analytic mathematical study which considers the trade-off between delivery probability and resource consumption for epidemic routing as optimal stopping rule of replication in opportunistic networks.

The paper has been accepted at the 3rd National Workshop for REU Research in Networking and Systems, which was collocated with the 6th International Conference on Computing, Net-

working and Communications (ICNC). In the workshop, each submitted paper has received at least 3 technical reviews from the TPC. 16 papers were selected for publication, which represent research progress of 11 different REU sites. The contributions of Salem Sati are the drafting of the methodology, solution and paper, as well as a joint development of the mathematical analysis part of the paper and the joint conduction of the experiments. Andre Ippisch implemented the policies and conducted a set of experiments to demonstrate its results. Kalman Graffi contributed to the methodology of the research as well as to the revision of the paper. Please note, that subsequent to the next verbatim copy of the accepted paper, we give an appendix in which a calculation step is elaborated in more detail.

Chapter 7

Replication Probability-based Routing Scheme for Opportunistic Networks

This chapter summarizes the contributions and gives a verbatim copy of our paper [SIG17]:

> Salem Sati, Andre Ippisch, Kalman Graffi. *Replication Probability-based Routing Scheme For Opportunistic Networks.* In Proceedings of the GI/ITG International Conference on Networked Systems (NetSys 2017), Göttingen, Germany, March 2017.

Also this paper addresses the problem of replication issues in opportunistic networking environments. The paper considers the replication as a heuristic problem to obtain an optimal replication decision based on the resource constraints. In contrast to our paper [SIG16], which we presented in Chapter 6, here we focus on an optimized scheduling policy instead of an optimized dropping policy. We propose a probabilistic forwarding scheme for opportunistic networks, called Replication Probability-based Routing Scheme (RPRS), based on controlled replication of messages aiming to keep a high delivery ratio while drastically reducing the message overhead. It uses from each single message two local parameters, replication count and hop count, to calculate the desired replication probability, which is used to prioritize the message for replication. Also, the proposed RPRS has its own drop policy whose utility function is calculated as a function of replication count, hop count, and the buffer time of a message which is considered being an estimate of the end-to-end delay. Through this, RPRS allows us to decide when it is desirable to further spread a message and thus reach a high delivery ratio without congesting the network with unnecessary message copies.

The main goal of this paper is to solve the question of how to implement an effective controlled flooding-based approach which drastically lowers the resource consumption and buffer congestion of greedy replication. This question is related to the dissertation's main question of resource conservation in opportunistic networking environments. Our proposed Replication Probability-based Routing Scheme aims to reach an optimal replication criteria for messages in the system with regard to maximizing the message delivery ratio while avoiding congesting of the network. The probability function of the scheme uses the message's hop-count, in addition to the node's local replication counter, where those two information characterize the message's overhead in the network. The buffer time is considered as storage and transmutation costs for the integrated drop policy. The replication and dropping criteria of RPRS are calculated based on local message information where this information indicates the minimum single message de-

livery probability. The idea of the proposed RPRS relies on the assumption that the best delivery ratio is achieved when the rate of forwarding is adapted to the dropping rate, thus the buffer stay optimally filled. The forwarding rate is adapted through a replication probability to control the number of messages spread in the network, which may then congest the buffers and be dropped. Therefore, RPRS considers the message's hop count and replication count for both forwarding and dropping as opposite functions.

The methodology of the paper is to propose the Replication Probability-based Routing Scheme using a mathematical model based on a Markov chain discrete model with ordinary differential equation, and its implementation and evaluation in the ONE simulator [KKO10]. The evaluation considers the end-to-end delivery delay and buffer time at relaying nodes as main component of end-to-end latency. Besides the metrics for the latency, we also consider the message overhead as metric for resource consumption in the network. We compare the performance of RPRS with two types of flooding-based opportunistic routing protocols, namely greedy uncontrolled epidemic routing protocol [VB00a] and Spray & Wait [SPR05] as quota-based controlled opportunistic routing protocol with a limit on the replication counter. Both routing protocols are tested with different replication and drop policies and compared to the proposed RPRS scheme.

As comparison, we select for both protocols of comparison different dropping and forwarding policies based on the idea of the proposed RPRS parameters besides their original dropping and forwarding policies. Based on our observations in [SPG16a], which we present in Chapter 4 we know that any policy must be adaptive to match the given opportunistic networking environment better. Obviously, the selection of the different policies is based on overhead variables, which are replication counter and hop counter of the message. This paper also considers the buffer time as main delay component for the drop policy. Therefore, the selected dropping and forwarding policies are based on the three variables of the message. From the suggested different policies of those variables, the paper selects a different drop policies such as FIFO (First-In-First-Out, minimum arrival time), MaFo (maximum replication count with a higher hop count as a tie breaker) and MaHo (maximum hop count). As forwarding policies for the epidemic routing we used FIFO, MiHo (minimum hop count) and MiFo (minimum replication count), which were very well performing in our overall study on scheduling policies in [SPG16a]. The evaluation analyzes the performance of the proposed RPRS scheme with different message TTLs and different buffer configurations. Our approach considers the replication as a heuristic algorithm to obtain the optimal replication condition which is taken as decision based on the resource constraints. The performance evaluation in this paper shows that the proposed RPRS performs better regarding the performance metric message delivery ratio as well as cost metrics such as overhead and buffer time in comparison to epidemic routing as an uncontrolled replication scheme and Spray & Wait as controlled (quota-based) scheme.

The GI/ITG International Conference on Networked Systems (NetSys) 2017 received a record number of 42 submissions for the conference, out of which 18 have been accepted (43%). The contributions of Salem Sati are the conception of the research, drafting the paper, as well as the development of the mathematical analysis part of the paper and the joint conduction of the experiments. The implementation as well as a set of experiments were made by Andre Ippisch. The methodology as well as the paper was revised by Kalman Graffi.

Chapter 8

Conclusions and Future Work

The objective of this thesis is to achieve a better message delivery ratio in opportunistic networks with reduced message delivery delay and message overhead. Regular opportunistic protocols such as epidemic routing [VB+00b] and Spray & Wait [SP05] fail to provide suitable message dissemination quality in opportunistic networks due to a high resource consumption by epidemic routing and long buffer delays by Spray & Wait. This thesis introduces first an overview on how protocols for opportunistic networks can be evaluated, second, provides a MAC layer configuration that maintains the neighboring node discovery quality while halving the signaling costs and then provides solutions for problems of routing and buffer management in opportunistic networks. The buffer management, i.e. the scheduling policy deciding which message to transfer upon transmission opportunity and the drop policy deciding which message to drop when the buffer is full, are analyzed in detail. In the thesis, we investigate the impact of 121 scheduling and drop policy combinations on the routing performance in various scenarios based on locally available message information, namely the message arrival time, time-to-live, replication count, hop count and size. The drawn conclusions on suitable buffer management strategies result in novel buffer management approaches on both flooding-based routing protocol (epidemic) and also on utility-based routing protocol (PRoPHET [GDLD11]). The two applied buffer management frameworks can effectively reduce the message delivery overhead and energy consumption while maintaining a very high message delivery ratio. Based on these two buffer management frameworks, the thesis is expanded to solve the routing problem by implementing a replication probability-based routing scheme which is suitable specially for high workload in opportunistic networks

8.1 Conclusions

Opportunistic networks are mobile, often wireless networks built of direct connections and often lacking of a complete path between source and destination nodes of messages. This environment requires relay nodes to provide sufficient buffer storage for messages for a long period of time, as messages often can only be forwarded one hop at a time with long delays to the next communication encounter. Traditional routing protocols for connected networks therefore cannot be applied in this scenario. For opportunistic networks new routing protocols following the store-carry-forward principle have been provided which are able to adapt themselves to this challenging environment. This new routing fashion often allows the further replication of messages in any sending node, hoping that one of these multiple copies reaches

the message destination. The simplest opportunistic routing protocols spread the message to every encountered nodes without having any selection criteria. In general, flooding-based opportunistic routing protocols can range from flooding the full network to flooding only a limited or controlled range. The unlimited flooding has its drawbacks such as it consumes the buffer space and inefficiently utilizes the available bandwidth. Those two drawbacks lead to a low message delivery as well as high energy consumption, which is the main resource of opportunistic nodes as hand-held devices. Other opportunistic routing protocols tend to limit the forwarding of messages by selecting suitable relay nodes such as used by controlled flooding and utility-based opportunistic routing protocols. These protocols compile information about the network topology and use this information to help the message carrier to identify more suitable contact partners than they are to route the message to its destination. These opportunistic routing approach fails when the network information is not sufficient for accurate decisions or the network topology is too dynamic. An efficient solution for opportunistic routing protocols should combine node selection, message selection, and buffer management mechanisms to achieve the best performance. Our contributions regarding the opportunistic routing challenges and the approaches to limit the resource consumption in this thesis, can be summarized as follows:

1. In Chapter 2, we discuss available evaluation environments for opportunistic networks with the perspective to also run more complex applications, such as chat or filesharing scenarios, on top of the opportunistic network. In [CAS+16], we discuss in detail the strengths and weaknesses of the main simulation environments for opportunistic networks, namely Opportunistic Networking Environment (ONE) [KKO10], DTN-Agent [VT10] and DTNSim2 [Wat06]. ONE is the most mature and also most used simulator for opportunistic networks, considering currently only simple workload models. We use ONE throughout the thesis for the evaluation of our further contributions. On the long term, we suggest in [CAS+16], that a more complex simulator, such as PeerfactSim.KOM [Gra11] should be extended to support both opportunistic networks as well as complex workload models related from the peer-to-peer field.

2. In Chapter 3, we proposed our solution [SG15] for establishing opportunistic wireless device-to-device connections using the Wi-Fi infrastructure mode. This is a promising field to gain many users for opportunistic networks, as commonly available Android devices support this approach for interconnection. We investigate the impact of the beacon interval in the process of announcing the presence of available access points. We propose the 2HKBI (Double Hundred Kilo Beacon Interval) approach, a modification to adapt the beaconing interval. It targets to reduce the control traffic by duplicating the interval of the traditional beacon. Our measurements show that the reduction of the beacon rate improves the channel utilization and lowers the energy consumption. Using 2HKBI maintains the connection probability at the same link establishment probability of the traditional beacon, while improving the performance metrics related to power and bandwidth. This step thus helps to conserve resources in the link establishment step in the opportunistic network while maintaining its quality.

3. In Chapter 4, we focus on the various possible strategies [SPG16a] for the selection of messages from the buffer, either for forwarding when a transmission opportunity exist or for dropping when the local message buffer is full. We considered both for the scheduling as well as for the drop policies information that is locally available in the messages, namely

message arrival time, time-to-live, replication count, hop count and size. Messages can be either selected based on the maximum or minimum values with regard to individual message parameters, thus resulting in 10 possible strategies both for the scheduling as well as the drop policy. Together with a random selection for both policies, we investigated the impact of 11·11 scheduling and drop policy combinations on the performance of epidemic routing in opportunistic networks. Simulation results show the performance of epidemic routing with regard to delivery ratio, message delivery delay and overhead ratio are quite diverse in the various scenarios. This study is very valuable to identify the impact and interdependencies of the various message parameters on the resulting performance of the epidemic routing protocol. It gives a guideline for implementing buffer management policies for flooding and utility-based opportunistic routing protocols, which we elaborate on in the next chapters.

4. In Chapter 5, we propose a new message scheduling and dropping framework (DFP-DDP) [SPG16b] for the prominent utility-based routing protocol PRoPHET for opportunistic networks. We develop buffer management policies based on the mechanism of the forward error approximation and dynamic drop policy. The decision of forwarding is made when the connected node shows a sufficiently larger delivery probability than the current node. This difference is calculated based on an analytic model we propose for the delivery probability of a single message. On the other hand, the drop decision for the buffered messages is made based on the utility function which considers the message information such as hop and replication counters, in addition to the time-to-live and buffer times. The simulation results show that the performance of PRoPHET routing protocol is improved by increasing the average delivery ratio and the implemented buffer management (DFP-DDP) also decreases the overhead which is considered as resource concentrate metric.

5. In Chapter 6, we formulate an optimization problem for epidemic as flooding-based routing protocols based on a Markov chain model. We solve the problem with two different objectives, namely minimizing the message overhead to conserve resources while maximizing the delivery ratio of the messages. Our solution in [SIG16] uses dynamic programming based on a stopping rule of message replication. Simulation results show that limiting the number of message copies achieves higher delivery ratio and minimizes the message delivery delay of the epidemic routing behavior. Limiting the number of replications further maximizes the number of delivered messages for nodes within a wide range of scenarios with limited buffer capacities, in addition to different traffic patterns and TTL values. Besides the good impact on the delivery ratio, also the transmission costs in terms of message overhead are drastically reduced, which is important in opportunistic environments, where bandwidth is scarce. While this paper focuses on the decision when and which message to forward, i.e. provides a forward policy, in the next paper we elaborate a suitable drop policy.

6. In Chapter 7, we propose our Replication Probability-based Routing Scheme [SIG17], which combines the strengths of two of the well-known opportunistic routing protocols which are epidemic routing and Spray & Wait. Our Replication Probability-based Routing Scheme provides better delivery ratio with lower network resource consumption. The scheme uses a stopping rule based on the message delivery probability as function of hop and replication count to estimate the route to the message destination, while minimizing the number of message copies throughout the network. Simulation results show that our Replication Probability-based Routing Scheme comes with less message overhead and

delay compared to both Epidemic as unlimited flooding and Spray & Wait as controlled flooding routing protocols while maintaining a higher message delivery ratio.

In conclusion, the dissertation's aim of improving the performance of connection establishment and routing in opportunistic networks with lower costs has been addressed with various contributions. In [SG15] we propose the 2HKBI approach which allows for a connection establishment on par with the current approach, while halving the signaling overhead. Through [SPG16a] we give deep insights in how the various individual message parameters can be considered in the decision which message to forward next and which message to drop when the buffer is full. Based on this study we provided routing protocols and schemes for message dissemination based on replication control and congestion control for the opportunistic environment. We improve PRoPHET's buffer management policies in [SPG16b] leading to an improved message delivery with lower costs. More generally, we aim for maximizing the delivery ratio and minimizing the resource consumption in flooding-based and utility-based routing protocols. Lowering the resource consumption is achieved by controlling the number of message copies which leads in improving the routing performance. In [SIG16] and [SIG17] we propose suitable message scheduling and forward policies as well as drop policies implementing this replication control, leading to less message overhead and higher message delivery ratios than the other well-known opportunistic routing protocols. We are looking forward to see these ideas influence the future upcoming opportunistic networks.

8.2 Future Research Plan

This thesis' work can be extended in future through several ways. Using partial differential equations instead of ordinary differential equations to model heterogeneous nodes instead of homogeneous nodes in the opportunistic network would allow to develop an adaptive routing protocol. The mobility models assume in most ordinary differential equations that all nodes are independent and identically distributed, where in reality there are scenarios where the nodes in the same group have different mobility patterns. Considering the possible mobility diversity in the models would allow for more reliable buffer management rules.

Up to now we considered only five message related parameters, namely arrival time, replication count, number of relayed nodes, time to live and message size for the buffer management. In addition, PRoPHET further considers the node's meeting rate and duration. In future, this list of considerable information should be extended with regard to the node facilities, such as buffer space, power budget or even compatible buffer management policy. In addition to the extension of the information basis, the buffer management policies must become adaptive. In [SPG16a] we have shown that depending on the scenario, i.e. the speed of the nodes, the message sizes and message creation intervals, totally different message parameters are ideal to be considered when selecting a message to forward or to drop. Once the arrival time of the message is important, once the remaining time-to-live, the replication count or even message size. It would be highly advisable to select the best suitable buffer management policy for each specific scenario we are in. For that, distributed monitoring approaches should be deployed which gather information on the network's status, so that nodes can assess what kind of network they are in and thus select the best buffer management policies related to this scenario.

In this thesis all opportunistic routing protocols assume that the nodes are fully cooperating, where in reality there might be selfish or malicious routing behavior. There are various motivations for the nodes to be selfish, such as to conserve energy or storage space. Malicious nodes might aim to sabotage the quality of the opportunistic network and the application that runs on. For the future, we suggest to consider in the creation of routing protocols and buffer management strategies the selfishness and routing misbehavior of opportunistic nodes.

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