Predictive Smart Relaying Schemes for Decentralized Wireless Systems

by

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Declaration

This thesis is submitted in partial fulfilment of de requirements for the degree of Doctor of Philosophy under the regulations set out by the Graduate School at the University of Warwick. I herewith declare that this thesis contains my own research performed under the supervision of Dr Mark S. Leeson, without the assistance of third parties, unless stated otherwise. No part of this thesis was previously published or submitted for a degree at any other universities.

List of Publications

Published Journals:

- B. Shao and M. S. Leeson, "Smart Relaying for Decentralized Wireless Networks," *International Journal On Advances in Networks and Services*, vol. 11, no. 1 and 2, Jun. 2018, pp. 57 – 70.

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Submitted Journals:

- B. Shao and M. S. Leeson, "KaFiR: Kalman Filter Routing for Unmanned Aerial Vehicles aided Decentralized Wireless Networks in IoT systems," *IEEE Internet of Things Journal*. (Under review)
- B. Shao and M. S. Leeson, "PaFiR: Particle Filter Routing – A Predictive Relaying Scheme for UAV-assisted Decentralized IoT Communications in Smart Cities," *IEEE Network*. (Under review)

Abstract

Recent developments in decentralized wireless networks make the technology potentially deployable in an extremely broad scenarios and applications. These include mobile Internet of Things (IoT) networks, smart cities, future innovative communication systems with multiple aerial layer flying network platforms and other advanced mobile communication networks. The approach also could be the solution for traditional operated mobile network backup plans, balancing traffic flow, emergency communication systems and so on.

This thesis reveals and addresses several issues and challenges in conventional wireless communication systems, particular for the cases where there is a lack of resources and the disconnection of radio links. There are two message routing plans in the data packet store, carry and forwarding form are proposed, known as KaFiR and PaFiR. These employ the Bayesian filtering approach to track and predict the motion of surrounding portable devices and determine the next layer among candidate nodes. The relaying strategies endow smart devices with the intelligent capability to optimize the message routing path and improve the overall network performance with respect to resilience, tolerance and scalability.

The simulation and test results present that the KaFiR routing protocol performs well when network subscribers are less mobile and the relaying protocol can be deployed on a wide range of portable terminals as the algorithm is rather simple to operate. The PaFiR routing strategy takes advantages of the Particle Filter algorithm, which can cope with complex network scenarios and applications, particularly when unmanned aerial vehicles are involved as the assisted intermediate layers.

When compared with other existing DTN routing protocols and some of the latest relaying plans, both relaying protocols deliver an excellent overall performance for the key wireless communication network evolution metrics, which shows the promising future for this brand new research direction. Further extension work directions based on the tracking and prediction methods are suggested and reviewed. Future work on some new applications and services are also addressed.

Nomenclature

AI	Artificial Intelligence
ANN	Artificial Neural Network
AODV	Ad-hoc On-Demand Distance Vector Routing
CGSR	Clusterhead Gateway Switch Routing
CRAWDAD	Community Resource for Archiving Wireless Data At Dartmouth
DARPA	Defence Advanced Research Projects Agency
DREAM	Distance Routing Effect Algorithm for Mobility
DSDV	Dynamic Sequence Distance Vector
DSR	Dynamic Source Routing
DTN	Delay Tolerant Network / Disruption Tolerant Network
DTNRG	DTN Research Group
EKF	Extended Kalman Filter
FaFiR	Kalman Filter Routing
FGAR	Fine-Grained Adaptive message Replication
FISST	Finite Set STatistics
FSR	Fisheye State Routing
GEO	Geostationary Earth Orbit
GIS	Geographical Information System
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GSM	Global System for Mobile communications
GT-ACR	Game Theoretic Approach for Context Based Routing
GUI	Graphical User Interface
HEO	Highly Elliptical Orbit
HIPERLAN	High Performance Radio LAN
HMM	Hidden Markov Model
HSO	Hybrid Satellite Orbit
HSR	Hierarchical State Routing
IC	Integarated Circuit

ICN	Intermittent ConNections
ICO	Intermediate Circular Orbit
ICT	Information and Communication Technology
IETF	Internet Engineering Task Force
IMM	Interactive Multiple Model
IoT	Internet of Thins
IRTF	Internet Research Task Force
ITU	International Telecommunication Union
KF	Kalman Filter
LANMAR	Landmark Ad Hoc Routing
LAR	Location Aided Routing
LPFR-MC	Location Prediction-based Forwarding for Routing using Markov Chain
LQG	Linear Quadratic Gaussian
LTE	Long Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MBM	Map Based Model
MCMC	Markov Chain Monte Carlo
MEO	Medium Earth Orbit
MIMOME	Multi-Input, Multi-Output, Multi-Eavesdropper
NASA	National Aeronautics and Space Administration
NoF	Network of Future
ONE	Opportunistic Network Environment
P2P	Point-to-Point
PaFiR	Particle Filter Routing
PEO	Polar Earth Orbit
PF	Particle Filter
PJA	Pilot Jamming Attack
PRNET	Packet Radio Network
PRoPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
PSA	Pilot Spoofing Attack
QoS	Quality of Service
RBM	Route Based Model

RBPF	Rao-Blackwellized particle filter
RF	Radio Frequency
RFID	Radio Frequency Identification
RNN	Recurrent Neural Network
RWP	Random WayPoint
SCF	Store Carry and Forward
SEBAR	Social-Energy-Based Routing
SIR	Sequential Importance Resampling
SIS	Sequential Importance Sampling
SMC	Sequential Monte Carlo
SPKF	Sigma Point Kalman Filter
SPMBM	Shortest Path Map Based movement Model
SURAN	Survivable Packet Radio Network
SVM	Support Vector Machine
TTL	Time To Live
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter
UMTS	Universal Mobile Telecommunications System
UWDTN	Underwater Delay Tolerant Network
VDTN	Vehicular Delay Tolerant Network
WLAN	Wireless Local Area Network
ZRP	Zone Routing Protocol

Chapter 1

Introduction

1.1 Background

More than 50 years ago, Gordon Earle Moore, co-founder of Intel, foresaw how the information technology industry would appear today by his “Moore’s Law” [1]. The realities prove that his rule is not only correct for the integrated circuit (IC), but also works for the affiliated software, applications and techniques. The exponential development of wireless communication technologies has made substantial changes to many people’s daily life. The variety of portable devices and smart gadgets, such as tablets, smartphones, digital cameras, wearable electronic devices and digital sensors, make its subscribers more reliant on digital systems and the Internet of Things (IoT) [2], augmented virtual reality [3], the tactile internet [4] and other sophisticated applications that attract users to remain attached to communication networks at all times. These applications facilitate the techniques of ubiquitous access [5] and pervasive applications [6]. Traditional radio systems can no longer satisfy this substantial number of traffic demands. There are unprecedented substantial issues to address to be compliant, although the 5th generation (5G) [7] of wireless systems is rolling out, and the 6th generation (6G) even the 7th generation (7G) mobile system standard are already on the horizon. As numerous various requirements from different customer sides for diverse applications and services, there is no sole technology can satisfy all the requirements, therefore, the collaboration of multiple techniques (multi-technology fusion) will be the solution.

There are clear advantages of wireless telecommunication technologies. Portable smart devices with wireless telecommunication adaptors using radio signal communication with others is becoming common. The users can share all kinds of resources and enjoy the convenience of high speed technologies all the time. However, despite systems with cutting edge techniques building up speed they can never ever catch up with the technology innovation and customer expectation with enough capacity to process their applications. Meanwhile, some states or places cannot meet the requirements needed to establish the wireless network and set up the wireless communication, especially the requirement for infrastructure or central administration or suchlike. Alongside these, the high-tech services and applications can also be interrupted by unpredictable incidents, interferences, natural disasters or sabotage. Thus, sophisticated designed solutions or concepts that differ from traditional wireless networks techniques are required to tackle these existing or potential issues or backup the communication system when the disruption occurs. When the centralized mechanism is not available, the decentralized wireless network becomes the only solution, which is a dynamical mobile network, and any nodes can join the network and leave the system at any time. In general, the applied scenarios of decentralised wireless network are military application, rescue mission, emergency services, space exploration, and home networking and so on. In this thesis, the proposed routing schemes deploy the decentralised mobile system into complex applications and services. The research work intends to tackle on some of the following existing issues and challenges, and increase the overall performance of wireless system under specific circumstances, applications and services.

1.2 Issues and Challenges

In order to accomplish a sophisticated design for decentralized wireless system, all aspects in respect of the targeted system and the current situation should be under scrutiny, which includes their strengths and weaknesses. In this section, the existing and potential challenges and issues of operated mobile system and decentralized wireless network will be carefully identified respectively as follows.

1.2.1 Issues of Operated Mobile Network

Despite significant amounts of investment in operated mobile systems, it is still relatively commonplace everyone for users to experience having no signal on their phones or portable digital devices. This could be caused by one or more of the reasons that follow below but there are other causes such as radio spectrum constraints [8].

- *Infrastructures*: lack of resources is always a potential issue for communication networks, in spite of their being well-designed in terms of a wired or wireless backup system. Even within the radio communication networks that have been widely deployed there are large numbers of places and circumstances where wireless subscribers can still suffer a lack of infrastructure to provide the basic connection intended, and the scenarios will be reviewed later in this work.

- *Interruption and Unavailability*: as mentioned above, there are many unpredictable disasters that could interrupt or destroy the operated communication system, which could be at the physical level (meaning the damage is unrecoverable) or only the logical level. The nature of radio frequency (RF) means that the radio signal can be influenced by the electromagnetic interference to varying degrees. Some loss can be recovered by channel coding or error correcting algorithms, but some can make the radio channel collapse. A strong geomagnetic storm can cause disconnection of communication or damage to electric equipment at the physical level on a large scale.

In the case of potential natural disasters (hurricanes, thunderstorms, earthquakes, landslides and tsunamis) and unpredictable incidents (power cuts, system failures, fire accidents, hacker or terrorist attacks and sabotage), the communication system is certainly vulnerable, and portable devices can only work under an ad hoc model [9], which is a type of decentralized wireless system, to achieve the information transmission.

- *Unbalanced Traffic*: emergency incidents or big events (concerts, festivals and sports matches) cause an extreme high density of population in a small region that can gather tremendous numbers of mobile phones, which leads to significant unbalanced traffic or burst data disaster. These can cause network congestion or further in system collapse. Backup methods or contingency plans are required to guarantee the normal operation of the system and give the network more robustness and resilience.

- *Radio Frequency Reuse*: RF is the most common transmission medium for the wireless communication system. The availability of RF spectrum is very limited, and only certain frequency bands are assigned to a particular communication standard to protect the resource from abuse and minimize the interference. Therefore, the limited frequency has to be reused. A good frequency reuse scheme is very important for the wireless network which can significantly increase the capacity of wireless networks, cut down the cost for each network user and the network service provider, and avoid interference between users to improve the quality of services and applications.

1.2.2 Challenges of a Decentralized Wireless Network

Given the tolerance and resilience characteristics of decentralized system, some issues of operated mobile systems can be solved by decentralized wireless networks that will be discussed in the following chapters. However, the decentralized wireless network faces many more challenges to achieve data transmission:

- *Infrastructures:* decentralized wireless networks face the severe challenge of lack of infrastructure and this is the cases in most application scenarios for decentralized mobile systems.

  a) Routers: there are no specific routers to route data packets between nodes. The traditional operated radio network has centralized routing strategies and each route in the network stores the route information and follows the same strategy to route data packets. However, in a decentralized wireless system, every portable node needs to act as a router to assist other network members to deliver data packets from the source node to the destination beside their own function design.

  b) Base station or access point: the decentralized wireless network does not, unlike the traditional wireless network, have base stations or access points which can cover the entire service area of wireless network territory, and all subscribers can move around the serving area freely. In a decentralized radio network, all nodes shall be able to service each other in each node's coverage area. The decentralized wireless network can expand the range of the network efficiently. However, if there are fewer nodes in the network, the range of the network could be small, which can decrease the efficiency of the system. In some circumstances, some paired nodes could be the bottleneck or the weakest link for the transmission.

  The implementation of a decentralized wireless network is easier, simpler and more flexible than the traditional wireless network. The decentralized wireless network does not need any fixed or prebuilt infrastructures when the wireless network is required. It can thus be formed at any place and the whole network can be moved anywhere.

- *Interruption and Unavailability*: although the decentralized wireless system is designed for dealing with the interruption and unavailability of operated networks, it still has its specified challenges. When the population of mobile nodes became smaller, candidate intermediate nodes are difficult to locate. The probability of messages can be received by its destination node could thus drop severely, for as long as the network remains sparse. Some portable nodes located at the edge of network serving territory could be unreachable for a long time. The protocol for decentralized systems needs to consider different network conditions to keep the system performance at an acceptable level.

- *Network Topology*: decentralized wireless network users can move to any place in the range of the network radio coverage. The states of the network will keep changing from time to time, for example, the location of the node and the quality of signal and so on. The signal will be influenced by the changing of the environment, place and topography. The coverage area of each node will be changed as well, so the topology of the network is easily changed (this will be discussed later). The node needs to work out the best next hop which can forward the data it received or produced by itself according to the different situations. But sometimes or in some places the signal could suffer from strong interference and then the quality of service cannot be guaranteed. In such cases, even the geographical relations of nodes could have changed or the air links do not exist and the network topology has changed.

- *Radio Frequency Coverage*: all wireless nodes can move around the network territory freely, the RF coverage shape of each portable device can keep changing all the time, the radio coverage pattern also changes. The radio link can only be created when two nodes are within the radio coverage range each other and the bi-directional connection has been set up. If the bi-directional link is disconnected, while data packets are transferring between two nodes, both must discover another available link to route the data packets to keep the communication working. Either the data packets are buffered by the mobile nodes, or both have knowledge about other routes in advance and the packets can be switched to another forwarding route.

- *Buffering*: the forwarding air link can be disrupted without any notice and the appearance of next available connection might entail an unknown wait time. The packet source nodes or intermediate forwarding nodes have buffer the message. However, the decentralized wireless network is formed from various devices, and some network elements have limited memory size to store the data packet. Even though smart terminals are powerful today, buffered messages cannot occupy a large capacity considering the normal utility of customer equipment.

- *Energy Consumption*: energy consumption has become a common issue since it encompasses most aspects of communications as these use power, here the problem is only limited to the battery of each mobile terminal. Mobile device design is driven by size and appearance with consideration of portability so the battery capacity cannot be very large. Smart devices in decentralized systems not only act as routers but also need to operate their own functions. The routing activities cause a reduction in battery life. The exhaustion of the battery causes the terminals to power off and will also affect the network topology.

  For the data packet forwarding tasks, the message holding node sends packets to the next hop in each relay. The data transmission costs energy to emit the signal between nodes, if the time of emitting can be reduced that can save mobile terminal energy. The design and optimization of the routing protocol can also affect the energy consumption of engaged smart terminals. The energy assumption issue is one of main concerns that will be identified in the following chapters.

- *Variety of Mobility Behaviour*: there is a variety of portable devices attached to the system. To achieve its designed application purposes, each terminal displays its own variety of motion. For instance, wireless ambient sensors are mounted at a fixed entity with a constant steady state; some onboard monitors or detectors have a regular movement route normally; the majority of mobile subscribers present a complex motion combination they can be a pedestrian or an onboard passenger or other state.

- *Other Embedded Resources on Mobile Terminals*: as with the embedded memory and battery, other installed resources on the mobile terminal are designed for their own functions and purposes, and the data packet forwarding tasks need to be considered. Therefore, the computational complexity of the message routing protocol needs to be cut down, which will protect the normal usage of mobile subscribers.

- *Quality of Service*: for a wireless communication system, quality of service (QoS) [10] is always the big problem, since the channel is unlike a wired network, with a physical cable or fibre having cladding and protection jackets to link all the equipment and guarantee that the signal can be transferred in a secured environment. The wireless medium technology that can be used in wireless communication includes infrared, RF, optical, ultrasound, etc.; these include numerous standards, such as, Wi-Fi [11], Bluetooth [12], ZigBee [13], WiMAX [14], Li-Fi [15] and so on. Even so, RF is the most common medium using the wireless communication since it can be relatively easily processed. However, the RF channel can be corrupted by various interference mechanisms that cause channel attenuation, including fast (short term) fading and slow (long term) fading. Flooding based on redundancy among forwarding groups may help overcome the channel fading, however, it will cause problems of efficiency for the radio system, and this aspect will be reviewed later.

- *Channel Bandwidth and Capacity*: the bandwidth and capacity of the radio channel is another system resource, and the bandwidth available for the wireless networks is limited. The state of mobile communication technologies is evolving rapidly. Compared with traditional wireless networks or wired networks, most mobile network routing protocols need more bandwidth to establish and maintain links between resource nodes and destination nodes to deal with the quickly changing nature of network.

  For decentralized wireless networks, the route of data transmission is formed by multiple radio links. Each radio segment has its own channel bandwidth and capacity. So, the information that can be transferred in the network links has a tradeoff between system information, user data packets and link capacity.

- *Data Packet Efficiency:* the efficiency of data packets is decided by the percentage of data payload in user packets. The data payload is the only useful part for user data, and it is the real bandwidth that can be used by network users. Because of the dynamic topology of the wireless system, its packets are needed to indicate changes in the network and this can reduce the payload ratio. Thus, the overhead of user data packets can be bigger and more complex as fewer bits are left for the data payload. This issue will be reviewed within the simulation work to present the performance of radio systems and evaluate the routing protocols designed.

- *Scalability of Decentralized Wireless network*: the decentralized wireless network is a dynamical network, which means any nodes can join the network and leave the system at any time. Therefore, it is very important for decentralized wireless networks that the network needs to have enough capability to deal with the change at any scale. This means the decentralized wireless network is allowed to grow physically by the addition of nodes or the expansion of the network radio coverage range, and vice versa. If the network is big, it will make the network structure very complex, which could provide more available capacity for the data packets to go through the network. However, the algorithm might need more time to work out the suitable path that adds to the latency of data packets and affects the QoS.

- *Uncertainties*: in a decentralized wireless network, given the freedom of mobile subscribers, each of the smart devices can move around the network area randomly. The wireless system benefits from the mobility of network subscribers to carry the data packets, however, which brings numerous uncertainties into the wireless network. For instance, the message carrying node has unsure movement direction that means that data packets could suffer unpredictable long delays; the best next hop changes every moment based on different criteria; the individual mobile radio signal pattern change caused by different ambient environments as the location changes. This puts the RF channel in an unpredictable condition and the radio coverage of the whole wireless network is different at every moment.

- *Security*: decentralized wireless networks are designed to be open wireless networks without centralized control, therefore, it is difficult to implement the security mechanisms used in centrally controlled or wired systems to achieve secured communications. Most decentralized wireless networks assume that all nodes are friendly (a closed user group), so the network protocol without security issues is considered. Any node can join the network anytime and anywhere in the range of the network without any protection. The node has no knowledge of the membership of other nodes, and there is no special network management or control equipment in the network to protect the security of the network and the nodes. It is difficult to determine the occurrence of impersonation attacks, and security prevention techniques are difficult at best. However, when the network membership is known and there is a danger of such attacks, some prevention techniques are needed to protect the control messages and some other important information. An assumption will be made in the later parts and will be reviewed in Section 1.6.

1.3 Solutions and Mechanisms

The growing demands of wireless communication facilitate the dramatic development of new technologies to tackle the resultant impact between connectivity needs and resources. There are some suggested solutions and mechanisms that can cope with the issues listed above.

1.3.1 Packet Switching

There are two communication switching methods: circuit switching [16] and packet switching [17]. The former needs the pre-allocated network resources for each switching session, and the QoS is contracted before the session is established and guaranteed through the entire session.

The latter is based on store-and-forward computer networking. All the information traversing the network is encapsulated into data packets. There are multiple switches and routes that relay these packets across the network. Data packet switching and message relaying techniques form the mainstream of solutions for decentralized wireless system.

1.3.2 Delay Tolerant Network

The decentralized system operates the wireless network in a decentralized manner and provides delay tolerant services to subscribers, to produce the so called wireless delay tolerant network or disruption tolerant network (DTN) [18] that is typical of decentralized wireless networks, in which the end-to-end connectivity is provided between a pair of nodes despite intermittent link connectivity and long variable delays between mobile nodes. It provides more network flexibility and resilience [19], therefore, the decentralized wireless network can be one of the solutions for opportunistic radio communication to tackle the occurrence of the extreme circumstances listed above.

1.3.3 Store Carry and Forward

In DTN wireless network, the end-to-end connections between a message source node and its destination are barely in existence, even the paired links between intermediate nodes are not always available. The message source node can either wait until the protocol forms the entire end-to-end route to deliver the message packet or choose the store carry and forward (SCF) relaying scheme [20]. For the former method, it is most likely impossible to create such an entire route in a sparse network [21] or a deep space communication network [22], as there is little opportunity for the network elements to stay on the chain of signal coverage at the same time to relay the message.

The SCF relaying scheme provides a more flexible solution to forward data packets. As its name implies, the message holding nodes store the data packet first if there is no further forwarding link available, and then carries the packet until the next hop appears, when the message is forwarded. This scheme offers more opportunities to let the message get through the network to reach its destinations.

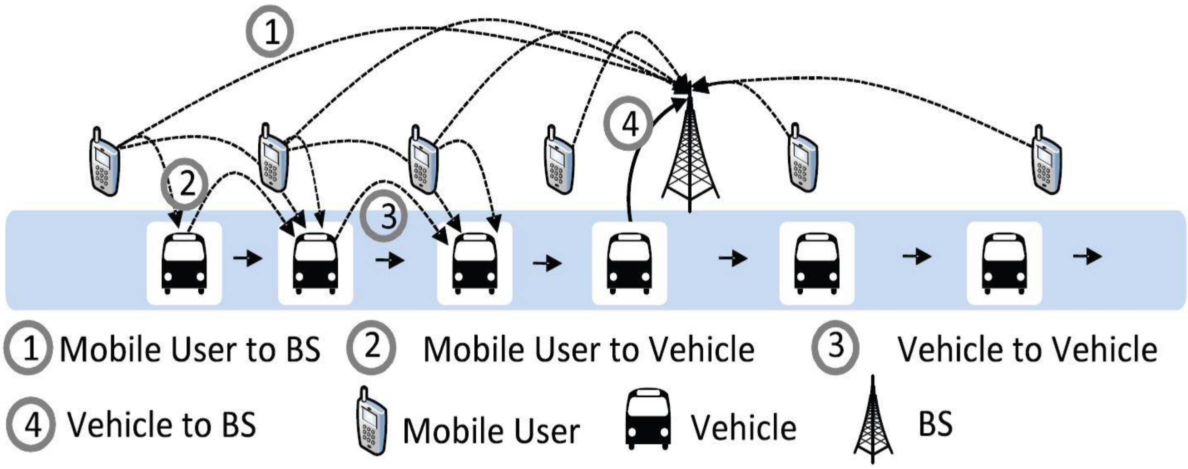

Fig. 1-1 Different multi-hop relaying realizations within the cell [23] (from Kolios et al., 2014).

Fig. 1-1 [23] demonstrates all possible relaying links, and how mobile users and vehicles cooperate and work as relaying routers to carry and forward data packets across the network.

1.3.4 Movement Prediction

The mobility of wireless subscribers is one of the benefits of mobile networks that provide more flexibility to mobile users. Moreover, it also allows portable device vendors to offer advanced functionality comparable to wired networks but in a much more adaptable and reconfigurable way. The SCF relaying scheme may use this mobility to achieve its relay work, whilst the nature of the random movements of mobile users bring uncertainties into the mobile network that could cause efficiency penalties from an unmanageable system, since most of the time there are no reliable end-to-end connections available for source nodes and their destinations. However, if the overall motion of wireless subscribers can be observed and the future movement can be foreseen, then the relay route is able to be well managed and optimized.

The acquisition of intelligence by modern portable nodes gives them the capability to analyse the ambient network situation. This provides inputs for routing decision making to assist the wireless system to improve its overall performance and ameliorate uncertainties caused by randomness. Recent developments in smart terminals have enabled mobile nodes to possess the required capabilities, and there are more rigorous prediction methods becoming available for the mobile terminals.

In modern mathematics and statistics, Bayesian algorithms are often used to encompass these uncertainties by inference approaches [24]. To predict the status of moving objects, the prerequisite is the measurement data and estimated data need to be defined under the dynamic state space model [25].

The Kalman Filter (KF) algorithm [26] [27] is an optimal estimation for dynamic system state by using the linear system state equation and observation data. Since the observation data contains the different of noise and interference, the optimal estimation can be regarded as a filtering process. The KF algorithm is rather simple to apply on the smart terminals.

The Particle Filter (PF) algorithm [28] is a recursive filter using the Monte Carlo method, which uses a set of weighted random samples that is called particles, to represent the posterior probability of a random event, from a sequence of noise contained or incomplete observations. To estimate the state of the dynamic system, the particle filter can be applied to models in any state space form.

1.4 Applications

The nature of decentralized wireless network is not designed to fulfil the needs of real-time services, for instance, voice calls or video calls. All of the information generated by the subscribers will be executed as data packets and relayed through the network to reach its receivers. There are many delay-tolerant services and applications, such as emailing, messaging, web browsing, social networking, blogging, etc. The technologies that can adapt the DTN services and applications are as follows:

1.4.1 IoT System

IoT is an emerging technology, there are as yet no firmly established definitions to provide a common terminology. In general, IoT is the technology to connect devices, vehicles, home and office appliances and any items embedded with an information collector (sensor, detector, scanner, etc.) according to a pre-agreed protocol to exchange and process information. The foundation of IoT technology is still Internet technology and its clients have extended to any items for information exchange and communication. All IoT clients are so called things, and the bearing network could be any computer-based systems that is a type of packet switch network which encapsulates the payload into data packets and relays these across the network. IoT and intelligent technologies are the very important part of a new generation of information technology.

1.4.2 Smart City

The concept of a Smart City [29] integrates various advanced technologies, especially information and communication technology (ICT), advanced digital devices and sophisticated designed services and applications, using a network, for instance the Internet or IoT technologies, to improve city conditions and provide convenience to its citizens. The Smart City integrates various resources and optimizes the urban planning and operations, which is an integration and innovation of new generation of information technology. The integration of IoT, ICT and other digital technologies furnishes bearing techniques to achieve urban intelligence, so the strength of the DTN system facilitates the growth of smart cities [30], which provides radio links to connect all elements into a wireless network with affordable cost. This will be elaborated in Chapter 5.

1.4.3 Unmanned Aerial Vehicle Assisted Network

The DTN system could be implemented into a broad territory and the mobility of network members causes changes of radio coverage pattern and network topology, which makes it hard to meet the mobile network ubiquity access requirements. The flexibility of the unmanned aerial vehicle (UAV) can assist the system to achieve fast implementation of the network [31].

The property of flexibility and adaptability of UAV aided solutions make them highly attractive in many communications applications and facilitates the development of the IoT and other future communication systems, this also provides opportunities to the network designer to deploy a complex network across a large region; these future network applications will be introduced in Chapter 7.

1.4.4 Other Scenarios

The rapid spread of computer network technologies lets delay tolerant services and applications be operated on many occasions, for instance emergency communications [32], wild animal studies [33], deep space robotic exploration [34] and so on. The applications for deep space communication will be reviewed in Chapter 8 as future work.

1.5 Motivations, Objectives and Novelties

The significant growth in communication technologies increases the utility of the emerging techniques of IoT, Smart Cities and UAVs. This provides unprecedented opportunities and demands to merge technologies and applications, and to contribute a united platform to fulfil the comprehensive needs of data processing and exchange. Powerful smart terminals facilitate more sophisticated routing protocols can be processed by each network element to complete the rigorous design.

In the mathematical and statistical domain, research on filtering methods continues to deepen and there are many valuable advances that have been made that are reviewed in [35] [36]. The optimized KF, PF and other filtering algorithms can be applied to complex systems with high efficiency. All these achievements motivate the research work on the existing issues and the development of integrated solutions for DTN systems.

The research objectives of this PhD thesis include:

a) New relaying strategies designed for decentralized wireless networks that target portable node motion recognition and prediction, using statistical reasoning to give mobile devices more intelligence to assist the DTN system, which are termed as the Smart Relaying scheme.

b) Protocols that enable intelligent terminals to observe the movement of adjacent wireless nodes so as to analyse the measured data and infer the targeted mobile subscriber motion strategies in different scenarios. This ability is of use within the SCF relaying scheme to create opportunities for the system to increase its overall performance.

c) Applying the proposed routing protocol into emerging and cutting edge technologies and applications, to adapt DTN technology for dedicated wireless communication systems providing solutions to meet diversified requirements for various services and complex scenarios.

The novelties of this PhD research are as follows. To the best of the author's knowledge this work is one of the first studies on adopting Bayesian filtering technologies into the portable terminal movement tracking to assist the wireless DTN system for making the routing determination and optimise the message relaying path. The outstanding simulation results show that the proposed design significantly improved the overall network performance with respect to resilience, tolerance and scalability.

1.6 Assumptions and Limitations

Decentralized wireless networks do not assume that any fixed infrastructure is available for the network, and a key element of this assumption is that not all nodes can directly communicate with each other. Hence, smart devices are required to relay data packets on behalf of other nodes in order to deliver data across the network to achieve the fundamental communication aims. Every individual mobile node may move to anywhere at any time, the topology of the decentralized wireless network and the link characteristics can change rapidly. Techniques are applied in the system which have to sort out all problems to establish the connection between any two nodes who want to communicate with each other and keep it working until the task is accomplished.

There are improved and extended approaches for the KF and PF algorithms that will be reviewed in this PhD thesis. However, as the limitation of length of work and the time, only the basic KF and PK algorithms have been developed as the routing strategies for the decentralized wireless network relaying protocols. The highly promising outcomes presented later show the suitability of these two algorithms for application in wireless relaying technologies. More candidate routing algorithms and strategies that could be applied for DTN systems will be introduced in Chapter 8 as future work.

In this chapter, general or overall assumptions and limitations are given as below. In subsequent chapters, there are some additionally identified assumptions and limitations that will be addressed with respect to particular issues in given scenarios and applications.

Some new technologies introduced in this thesis have not been standardized firmly, such as the latest applications mentioned in Chapter 7. Thus, the proposed protocols are based on generic concepts and system structures not international standards since these are not available yet.

1.6.1 Radio Frequency Link

Two adjacent nodes communicate directly using their radios, but one of these two may have a more powerful transmitter than the other or their receiver sensitivity are different. The configuration is illustrated Fig. 1-2, in which it is possible that node A can connect to node B, but node B cannot reach node A, giving a unidirectional link only. However, for simplicity, in this thesis it is assumed that all of links between any pair of adjacent nodes are bidirectional and symmetric. If any node moves to the edge of the network range and cannot communicate bi-directionally with any other node, then it becomes unreachable as is the node H in Fig. 1-2.

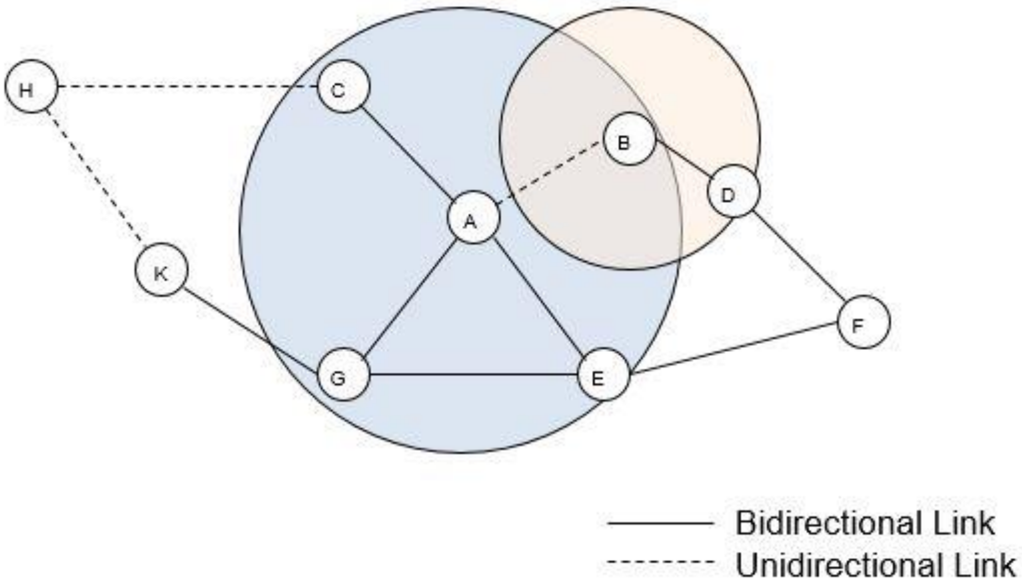

Fig. 1-2 An example topology of a decentralized wireless network.

Moreover, the bandwidth of all available bi-directional radio links between any two nodes is assumed adequate to bear the data traffic and to comply with the requirements of bearing services and applications.

1.6.2 Resources

Limited resources are the issues of decentralized mobile systems that were revealed in Section 1.2.2. However, when a data transmission is taking place with a node, resources are assumed to be adequate to support this transmission until it is complete, or the physical link is disconnected. The resources include embedded memory, processor, battery, peripheral equipment and so on.

1.6.3 Issues not Considered

Medium access control (MAC) [37], routing QoS and higher layer applications are not considered in this PhD thesis, however, these open issues are still a critical part of the whole set of DTN routing protocol projects. They are thus reviewed as future work in the last thesis chapter.

Similarly, data errors from lower layers will not be considered in the wireless routing protocol designed, as these are assumed to be corrected by the lower layer transmission protocols, such as channel coding, error detection and error correction algorithms [38].

1.6.4 Services and Applications

Given the nature of the PhD, the proposed solutions concentrate on solutions applicable to issues and challenges of interest identified in Section 1.2.2. The routing protocols are designed to facilitate the applications listed in Section 1.4. The design scenarios used contain only delay tolerant services in their operation, and it is assumed that all these services can be borne by the resultant routing protocol.

1.6.5 Security

Since this is a fundamental study, there is no management mechanism applied to the system that may cause severe decentralized wireless network security difficulties. Thus, security issues will be not considered in the proposed routing protocol. It is thus assumed that security mechanisms are implemented either in the physical layer, within the application or using some combination of both. Aspects of security will be reviewed in Chapter 2.

1.6.6 Fairness

All mobile nodes join the network are assumed to fully obey the principle of a given relaying scheme as it dictates, which means the fairness of message delivery in the system [39]. For the design of the proposed protocol, the strategy guarantees that the system will not cause any bias in any terms. Every user and all data generated by any nodes in the specified radio network are treated equally.

1.7 Thesis Organization Structure

The first part of the thesis gives a prologue on decentralized wireless network, the relevant challenges, candidate applicable technologies and applications. These aspects cover the majority of the PhD research work.

The remaining parts of this thesis are organized as follows. Chapter 2 provides a literature overview of existing decentralized wireless network routing techniques, prediction approaches for assisting routing decision making and suitable applications and scenarios. Chapter 3 introduces the principle of DTN routing protocol design and the simulation process that includes an introduction of a JAVA based simulator. Chapter 4 gives detailed information about the proposed KaFiR routing protocol regarding routing strategies, aims and an explanation of the mathematical model, meanwhile, the simulation of the proposed protocol and a comprehensive comparison between KaFiR routing schemes and other DTN routing protocols are also given. The application of the KaFiR protocol for UAV assisted mobile IoT systems in smart cities is presented in Chapter 5. Chapter 6 includes the scrutiny of the PF algorithm and PaFiR protocol, and Chapter 7 describers the study of PaFiR applied in a complex future network. The final Chapter presents conclusions and addresses some suggestions for future work, in particular ongoing research in space communication.

1.8 Summary

This chapter gives an overview of the work that will be detailed presented in this thesis. First, the issues and challenges of decentralized mobile systems have been identified clearly and this is followed with description of the solutions and suggested mechanisms. After that, there was coverage of the appropriate applied scenarios and services are of interest to the proposed DTN routing protocols, which form the motivations and objectives of the thesis. For fundamental simulation and design research, some assumptions and limitations have to be made as pre-conditions and these were expounded. Finally, the thesis organization structure was presented to outline the content of each chapter.

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Chapter 2

Literature Review

2.1 Introduction

There are two main terminologies for decentralized wireless networks: DTN [1] and MANET (Mobile Ad Hoc Network) [2] [3]. They both tackle the issues of infrastructure shortage and intermittent radio links, and propose their solution in different ways.

2.1.1 Delay Tolerant Network

The rapidly growing demands of wireless communication facilitate the fast development of new technologies to tackle the impact of connectivity needs on resources. The data packet switching and message relaying technologies are the mainstream solutions to solve the problem of operating wireless networks in a decentralized mode and provide delay tolerant services to subscribers. Zhou and Zhuang [4] reveal the characteristics of decentralized wireless networks in which the network elements perform cooperative communications. The concept was first introduced by Kevin Fall, a former principal researcher at Intel Corporation at the beginning of 21st century and his paper [5] defines the network architecture and application interface of wireless DTNs. This milestone paper won the SIGCOMM test of time paper award in 2013. Since then, a dedicated DTN Research Group (DTNRG) [6] was established by the Internet Research Task Force (IRTF). In the last decade, there are many institutes and organizations that have performed a substantial amount of research and contributed various proposals [7].

For DTNs, there is no prerequisite of end to end connections at any point in time, however, the message packets pass through the network with intermittent connectivity [8]. The unpredictable delay could occur at any intermediate forwarding point along the relaying segments. The dedicated routing protocols for DTN will be reviewed in the following chapters.

Different types of DTN systems apply for various application purposes, for example Vehicular delay tolerant networks (VDTNs) [9], Underwater delay tolerant networks (UWDTNs) [10], and so on.

2.1.2 Mobile Ad Hoc Network

DTN and MANET are both in the family of decentralized wireless networks. They cope with a similar network condition that has no fixed infrastructure available or where the infrastructure is impractical, expensive, untrustworthy, or has no pre-determined organization of available links. The MANET can be used for military applications, rescue missions, emergency services, space exploration, home networking etc [11].

MANETs have a much longer history than DTNs. The Packet Radio Network (PRNET) [12] can be seen as the first generation of the ad hoc network, which was sponsored by the Defence Advanced Research Projects Agency (DARPA) [13]. It can be traced back to 1972 and evolved into the Survivable Packet Radio Network (SURAN) program in the early 1980s [14]. The techniques were controlled by the government and only applied in some military areas. In the early 1990s, notebook computers became popular. More attention became focused on infrastructureless wireless networks and the IEEE 802.11 [15] subcommittee adopted the term “ad hoc network” which is the first non-military use of the concept of an ad hoc network. In the late 1990s, the MANET became one new working group in the Internet Engineering Task Force (IETF). It engages in standardizing ad hoc network routing protocols. High Performance Radio LAN (HIPERLAN) [16] and Bluetooth [17] were some other standards that addressed and benefited ad hoc networking.

There are many different routing schemes that have been developed for MANET protocols. These resulted in a range of routing protocol proposals that are designed for different network deployment purposes and these will now be discussed.

- Flat routing schemes [18]
    - Proactive (table driven) protocol: The protocol keeps track of routes for all destinations in the ad hoc network, which can minimize the initial delay, but it adds plenty of control traffic to the ad hoc network. Protocols include Dynamic Sequence Distance Vector (DSDV) and Fisheye State Routing (FSR) [19].
    - Reactive (on demand) protocol: The protocol is designed so that when an actual route is needed, the routing information is required. This protocol uses far less bandwidth to maintain the route table of each node than

    proactive protocol. Protocols include Ad-hoc On-Demand Distance Vector Routing (AODV) and Dynamic Source Routing (DSR) [20].

- Hierarchical routing schemes
    - The protocols are based on the idea of organizing nodes in groups and then assigning nodes different functionalities inside and outside a group. Both routing table size and update packet size are reduced by including them in only part of the network; thus, control overhead is reduced. Examples include Hierarchical State Routing (HSR), Clusterhead Gateway Switch Routing (CGSR), Zone Routing Protocol (ZRP), and Landmark Ad Hoc Routing (LANMAR) [21].
- Geographic position assisted routing schemes
    - This routing scheme needs to use GPS (Global Positioning System) to provide the location information and the universal timing. The location information can be used for directional routing in distributed ad hoc systems; the universal clock can provide global synchronizing among GPS equipped nodes. Examples include Location Aided Routing (LAR), Distance Routing Effect Algorithm for Mobility (DREAM) and Greedy Perimeter Stateless Routing (GPSR) [22].

2.1.3 Comparison with Conventional Wireless Networks

In the traditional wireless networks currently in use, it is normal for only mobile subscribers move around the network service area, whereas the mobile base stations, also known as wireless access points, are fixed in one place. These systems are characterized as centralized wireless systems such as Wireless Local Area Networks (WLANs), the Global System for Mobile communications (GSM), the Universal Mobile Telecommunications System (UMTS) and Long Term Evolution (LTE) [23]. Most centralized wireless networks are operator controlled systems and subscribers are charged for using services, with dedicated network resources allocated through the entire session so that services and applications can be guaranteed when they are required. The serving territory relies on the radio coverage area of the base stations and cannot easily influenced by the other elements. The system capacity is limited by the infrastructure implemented and the resources assigned for the system. Any network expansion needs investment in more facilities and resources, for instance equipment, licenses, radio spectra, sites and so forth. The conventional wireless network has more reliability but less flexibility and a high cost for implementation and maintenance. Service subscribers do not participate in any data transmission tasks.

In DTNs and MANETs, there are no dedicated base stations acting as servers for the subscribers. Every portable node not only has a role as a user but also works as an intermediate transmitter, which means it needs to route the data for other nodes. As a bearing network, its subscribers are not charged for connections provided by the network but there could be some fees from service or content providers. DTNs and MANETs are both open and non-management mobile systems that have high flexibility and lower cost for implementation and maintenance but less reliability. Each of network member is potentially required to assist in the data transmission for other subscribers.

2.1.4 Why DTN?

In this PhD thesis, a predictive relaying scheme is proposed using different reasoning techniques that gives the individual smart devices the power to determine how to assist other network numbers for message forwarding.

For MANET routing, when the source node generates a message, this node finds an end to end route to reach the destination based on its knowledge of the network topology. The routing decision is made by the source node, and the intermediate nodes in the forwarding pass only transfer the data packets transparently.

The DTN routing operates using the SCF routing strategy. The source node stores the generated message first before it starts seeking the appropriate relay node, and the source node is only responsible for determining the first hop on the message routing path. If there are intermediate mobile devices involved the relaying process, each of them has to seek the next hop by their own decision to forward the packets. This store, carry and forwarding process requires each of the engaged elements to use their knowledge to identify the appropriate forwarding node during the store and carrying stage. The essential difference between MANET and DTN routing strategies is that the latter allows each relaying participant to use its estimation to determine the packet route. This provides opportunities to apply a prediction mechanism into the routing protocol to optimize the data packet relaying route and make smart relaying possible.

2.2 Routing schemes for DTN

To deal with the motion of mobile nodes within a DTN, it has been common to form routing paths between nodes that are in each other's direct communication range [7]. Thus, the network needs to maintain an end-to-end structure whilst its intermediate structure varies with node movement. This is difficult because variations in node positions constantly change the underlying communication graph and mean that nodes must quickly adapt to the new configurations. One of the methods for solving this problem is link reversal [24], which models the problem as a directed graph, reversing the link directions when needed as a result of motion induced connection loss. Unfortunately, as shown in [24], the time to produce a stable link for communication grows as the square of the number of nodes in the network, limiting the scalability of such algorithms. As a result, the SCF approach [25] was developed, in which intermediate mobile nodes store messages in their local memories if they do not encounter a suitable relay node. The messages are then carried whilst the nodes move until they find an appropriate node to which they can forward their data towards the destination.

Early DTN protocols such as epidemic routing [26] operated without network information to aid their decisions. The target in such an approach is to spread packets rapidly throughout the network without a node selection criterion (that would need extra information). Packets are copied at all node encounters and persist in the network until they reach their destination or exceed a chosen lifetime. Protocol performance drops with increasing load because of the growing demands for storage space and low probability that useful forwarding nodes will be encountered rapidly. Limiting the number of copies permitted was introduced by protocols such as Spray-and-Wait (SnW) [27]. In this method, once the maximum number of copies is reached, the carrying node keeps the packet until it reaches the destination, storage limits are exceeded or the packet times out. To overcome the limitations of the random approach above, many protocols have been developed that collect network information to select relay nodes enhancing delivery probability despite limited storage and energy resources [1]. A well-known example of a protocol that predicts contacts among DTN nodes is PROPHET [28]. This produces a node metric via the number of meetings between nodes; the link weightings between nodes are increased when they meet along with the weightings of other nodes that they have met. The adoption of this method produces an increased delivery ratio but at the price of an increased average packet delay. The information gleaned from node interactions may also be used to detect what can be described as *social* relationships between the network nodes [29]. These formalize the concept that to be considered part of the same community, nodes should be in frequent, regular and long-lasting contact that will suggest promising forwarding paths. For brevity, the summary above naturally leaves out many variations on the themes presented, so the interested reader is referred to [30] for further details and references.

With particular reference to uncertainty in wireless subscriber movement prediction, it is known that given knowledge of a large population, accuracies approaching 90% can be achieved [31]. However, here the need is for real-time estimation based on limited information. Sometimes, the DTN in question will have movement restrictions such as that considered by Ahmed and Kanhere [32]. They considered operation where public transport networks or street patterns reduced the range of subscriber movement choices to simplify the prediction work. In general, the networks nodes must be allowed more freedom and the approach taken can be reactive or proactive [33]. In the former, nodes report their location to a central network authority such as a base station. However, in the latter, prediction is used with the potential to reduce the inevitable latency whilst waiting for location updates. The uncertainty arises from the mobility model extending into the future based on known mobility history data. The success of a mobility model depends on how well it can learn and predict future node locations based on the available scenario history [33]. User movements are to a large degree predictable [34] so the problem becomes one of designing an efficient location prediction algorithm using past data.

Similarly, the idea of using prior probability and Bayesian inference to properly drive a search process in ad hoc delay tolerant networks has been exploited [35]. This use of a generic computable inference mechanism to increase the performance of DTNs has gained popularity in the last few years, culminating in a recent study employing a weighted feature Bayesian predictor that outperforms a naïve Bayesian approach [36]. However, there is no comprehensive and systematic research study on the entire system to improve the network performance by using rigorous prediction and analysis methods. Although Kalman filtering has been used to update connection probabilities [37], the work in [35] was the first adoption of Bayesian inference, in the context of DTN routing. However, the main focus of the paper is on gradient routing in which the message tends to follow a gradient of increasing utility function values towards the destination. Another paradigm has been employed by Talipov et al. [38], who utilize a hidden Markov model to predict to predict the future location of individuals. The inspiration for the scheme is the same as the one in this thesis and is based on the observations of Gonzalez et al. [39] that human trajectories show a high degree of temporal and spatial regularity, and in social environments individuals move subject to a deterministic schedule with only a few random deviations.

Based on relaying strategies, DTN routing protocols can be classified as: single-copy schemes (forwarding-based) and multiple-copy schemes (flooding-based or semi flooding-based) [40]. Single-copy routing protocols maintain a sole duplicate of each message as it forwards in the system. These protocols require fewer system resources, however, this strategy could have a low delivery probability and large latency. Multiple-copy forwarding schemes have more than one duplicated copy of signal data packets. Some multiple-copy protocols flood the copy to each of the mobile nodes encountered that do not have the message. The scheme attempts to increase the delivery ratio by maximize the number of duplicates but it occupies and wastes large amount of network resources in addition to decreasing the system efficiency. Regarding this problem, some protocols try to control the flooding process and reduce forwarding duplicates [41].

2.3 Existing Routing Protocols

There are many existing routing protocols that could be applied in DTN systems. In this work, the following routing strategies will be reviewed and compared with the proposed Smart Relaying algorithm to present its performance for various network scenarios.

Direct Delivery routing protocol [42] also known as the Direct Transmission protocol, in which the sender only delivers the message to the final receiver directly as soon as an encounter happens. There are no other intermediate nodes involved in the packet relaying offering advantages when there are no reliable intermediate nodes available. The protocol is able to securely deliver the information with minimum overhead ratio and transmission energy consumption. However, the delivery probability relies on the likelihood of node encounters, which determines that this routing scheme is only appropriate for some particular scenarios or requests.

Epidemic routing protocol [26] is based on a simple flooding mechanism to relay the data packets. As its name implies the relaying strategy is to maximize the delivery probability by spreading messages as an epidemic disease to any mobile nodes it encounters that has not already stored them in its buffered message list. This mechanism causes a substantial waste of buffer capacity, air interface bandwidth and transmission energy to flood the packets. If the network is experiencing a high traffic volume, this protocol could affect the normal usage of mobile subscribers or the efficiency of the wireless system.

PRoPHET (Probabilistic Routing Protocol using History of Encounters and Transitivity) routing protocol [28] is one type of encounter history based prediction packet relaying scheme, which considers the delivery predictability of node encounters and transitivity to select and forward data packets to the desired neighbouring nodes.

Spray and Wait routing protocol [27] has two versions: Binary and Vanilla. In this work, the widely applied Binary version only is considered for comparison with the proposed routing protocol and other candidate protocols. As indicated by its name, Spray and Wait consists of two phases: a Spray phase and a Wait phase. In the former, a source node transfers half of a replicated message to the first node it encounters, then the relay node forwards half of replicated packets to future nodes encountered, until a node has only a single copy of message; the latter phase is entered at this point and a direct delivery strategy is used to deliver the data packet to the final receiver.

Spray and Focus routing protocol [43] is the upgraded relaying strategy of the Spray and Wait protocol, to tackle some problems with that scheme by introducing a new second phase, called the Focus phase, instead of the Wait phase. When a node only has one forwarding token left for a message, Spray and Focus routing no longer waits for the direct delivery opportunities but rather each relay can forward its copy to a potentially more appropriate node, using a sophisticatedly designed utility-based scheme.

LPFR-MC (Location Prediction-based Forwarding for Routing using Markov Chain) routing protocol [44] uses a Markov Chain to predict the probability of a targeted mobile node moving towards the destination location or region of a relayed packet. The computation is based on the present location of a portable node and the angle between itself and its intended destination, to determine the next hop forwarding the message segments.

FGAR (Fine-Grained Adaptive message Replication) routing protocol [45] uses repeated patterns to improve the algorithm prediction accuracy as contacts among subscribers have a high degree of repetition because of the similarity of mobile users’ daily routines carrying portable terminals.

SEBAR (Social-Energy-Based Routing) routing protocol [46] uses the mobile node social energy in its encounters. The more interactions that a node has, the higher its social energy will be. When a node encounters another node, the protocol favors the social community with the higher social energy, either that of the original node or that of the destination.

GT-ACR (Game Theoretic Approach for Context Based Routing) protocol [47] relies on a non-zero sum cooperative game of two players assisting with the context information, encounter index, and distance of the corresponding node from the destination as vital attributes in framing the game, to select the best possible relaying node.

Some of the above reviewed routing strategies fully depend on the dissemination of data packets that can cause a substantial waste of network resources and some problems or risks in the wireless network, such as radio bandwidth, buffer and battery life of terminals, and furthermore network congestion. Some prediction-based relaying protocols are highly reliant on history records that require a large memory capacity to store the history data. Even though modern smart devices embed substantial memories, batteries and processor power, extremely large hardware usage requests can still cause substantial impacts on the normal function operation of terminal users. The ideal routing scheme needs to provide an optimized relaying path for the message to obtain network service and maintain a high performance of the wireless system, whilst meanwhile keeping the occupation of resources on the working portable terminals as low as possible.

2.4 Movement Prediction Techniques

Movement prediction actually describes the process of tracking and reasoning within the moving objects based on a mathematical and statistical model. This is a well-studied area, in which numerous pieces of research have been carried out for military and non-military applications in the past decade. Those technologies have been the essential part in many areas, for example, vehicle surveillance [48], GPS based navigation [49], autonomous robot control [50], object tracking [51], location services [52], aviation management [53], aeronautical and astronautical engineering [54].

There are many different mathematical and statistical methods to track and predict the targeted object movement. In [55], a Viterbi algorithm of Hidden Markov Model (HMM) is introduced to track multiple targets by Ardo et al. The KF [56] and PF [57] algorithms have had significant applications in moving object tracking, and consist of a series of filtering, prediction and smoothing operations to carry out the online tracking using the relevant model. In the modern statistical and mathematical approach, all these movement prediction techniques are based on recursive Bayesian logic [58]. As a consideration of application scenarios and processing capability of mobile terminals, the KF and PF methods are selected for this research work.

2.4.1 Bayesian Approach

The tracking problem is to determine the state of targeted moving objects that includes their locations, velocities, accelerations, paths and other characteristics. This estimation process can be formed into a Bayesian probabilistic framework [58]. The classical Bayesian approach provides a method to deduce the further states of observed moving objects. Bayes' theorem [59] implies that the mobile object states can be predicted from the observation data, which is the joint probability of the state of event and the observation of event divided by the unconditional probability of the observation of event.

2.4.2 Kalman Filter

Filtering estimation technologies derive from the method of least squares [60] that has been recognized as the first breakthrough in estimation methods as an approach to regression analysis [61]. In 1795, Gauss proposed his classical theory in [62]. This estimation method did not consider the statistical characteristics of the parameters, due to its calculation being rather simple, it has been widely used in many research areas. Fisher proposed the maximum likelihood estimation based on the idea of probability density in [63], which was a significant contribution for solving the estimation problem, however, there was no research about the estimation of random processes at that time. These were included by Wiener as he invented a statistical optimal filtering method that applied a frequency domain method to solve the problem of least squares optimal filtering [64]. In 1960, Rudolf E. Kálmán, a Hungarian-born American electrical engineer, created his classical Kalman Filtering (KF) that can be applied to the optimal discrete-time linear filtering problem [56], which eliminates the restriction of the Wiener filtering algorithm [65]. The KF algorithm is an optimal prediction and tracking algorithm, and since then it has been applied in various applications. In 1961, Kalman and Bucy extended the application of KF from discrete-time to continuous-time systems [66]. When Kalman was working for NASA (National Aeronautics and Space Administration), he found that his method was useful for resolving the orbit prediction of the Apollo project. Later, the Apollo spacecraft's navigation system used his filtering method.

In the following decades, the KF algorithm was substantially improved by contributions from many researchers. Bucy and Senne [67] and Sunahara and Yamashita [68] developed an Extended Kalman Filter (EKF) which can be adapted for nonlinear stochastic discrete systems. The Unscented transform is used to approximate the joint distribution that is core concept of the Unscented Kalman Filter (UKF) which was created by Julier and

Uhlmann [69] and Julier et al. [70]. Merwe and Wan use the Sigma point developed Sigma Point Kalman Filter (SPKF) [71].

The KF is one of the object tracking algorithms based on the Bayesian approach to solve the reasoning and filtering problems, and the estimation method applies Gaussian approximations. The motion data are processed by the KF algorithm that can be seen as a series of prediction, tracking and smoothing calculations of the movement of a targeted moving node. In general, the terminologies of different estimation process are according to the moment of all measurements of the tracking target. Tracking is also referred to as filtering that is to estimate the current moment state of targets. Smoothing accesses the past status of the movement, which assists to correct the error in previous stages. Evaluating the future motion of the tracked object is prediction [72]. These characteristics provide opportunities to the proposed routing protocol to track and predict the diversified movement of targeted mobile nodes and UAVs, and to assist the message store and carrying node in finding the best intermediate hop to optimize the data packet forwarding route in various complex scenarios with regard to the movement of things within the network territory. In a mathematical form, all these processes can be described as different distributions that will be discussed in Chapter 3.

Although the KF algorithm is one of the optimal prediction and tracking methods, it is only applicable to the case where the filtering error and the prediction error are small, otherwise the initial estimation of the covariance drops too fast, which may cause the filter to be unstable or even divergent [73]. That requires a more rigorous filtering algorithm to tackle more complex scenarios. The approximation method is to use the probability to approximate the likelihood, which can be formulated as the probability distribution. When the tracked object moving in a complex condition, the formulated probability distribution becomes far from a Gaussian form, so Gaussian approximations are not appropriate. These scenarios need a multiple model instead of the method introduced with the KF. The alternative solution to cope with this complexity is to consider Monte Carlo approximations.

2.4.3 Particle Filter and Related Technologies

The core concept of the particle filter (PF) algorithm is the Monte Carlo algorithm that was proposed by Ulam and Neumann who were members of the "Manhattan Project" program that the United States developed the atomic bomb in the Second World War in the 1940s. The mathematician von Neumann named this method by taking that of the worldfamous casino, Monte Carlo, Monaco. Prior to this, the Monte Carlo method already existed. In the 18th century, the French mathematician Buffon proposed to use the method of needle injection to find the value of π. This is considered to be the origin of the Monte Carlo method. [74]

In the past decades, a considerable amount of research work has been carried out in the area of nonlinear object movement tracking to enhance the algorithm and adapt it to more applications, covering many methods of nonlinear filtering based on Bayesian estimation. Hammersley et al. proposed the basic sequential importance sampling method in 1954 [75], which is the essential filtering concept of Bayesian sampling estimation for nonlinear filtering. In 1993, Gordon et al. proposed a Bootstrap nonlinear filtering method based on a sequential importance sampling method [76]. The recursive process overcomes the degeneracy phenomenon of the sequential importance sampling algorithm. In 2000, Doucet et al. gave a comprehensive description of particle filtering based on sequential importance sampling using the Monte Carlo method to solve Bayesian estimation [77]. Multiple integral operations and the use of sequential importance sampling technology delivers a set of particles in the dynamic state space, each of which corresponds to an importance weight; finally an estimate of the state posterior probability density is obtained by weighting the particles together. This method became the foundation of the particle filter algorithm and led the extensive research on sequential importance sampling. For a complex scenario with multiple nonlinear object tracking, Doucet et al. used a Rao-Blackwellized technique to coin Rao-Blackwellized particle filters (RBPFs) [78].

The PF algorithm applies the Monte Carlo method to formulate a distribution that is similar to the real posterior probability density function of the state variable, which let the PF to be applicable to any non-Gaussian and nonlinear stochastic system and adopt into complex scenarios and applications.

2.5 Applications

The proposed decentralized wireless network routing protocols aim to integrate the KF and PF algorithms into the packet relaying route decision making to overcome the issues and challenges have been revealed in section 1.2.2, and apply it into the applications and scenarios as follows:

2.5.1 Mobile IoT

In 1999, the phrase Internet of Things was first coined by Kevin Ashton, a British technologist, who worked for the MIT AutoID lab when he was studying on RFID (Radio Frequency Identification) technique [79]. This led to an initial understanding of IoT in the context of RFID-based systems. In 2005, an Internet report [80] issued by the ITU (International Telecommunication Union) changed the definition and scope of the IoT, and expanded its meaning to no longer be based solely on RFID technology. The first international IoT conference took place in Zurich, Switzerland from 26–28 March 2008 [81]. RFID, short-range wireless communications, real-time localization, and sensor network technologies are introduced into IoT applications formally by multiple academic publications. The deployment of IPv6 in the 2010s facilitated the development of IoT applications, since IPv6 features make it possible to allocate IP addresses to all the things connecting to the network to build the IoT system [82].

In practice, IoT services and applications are often supported by various wireless communication technologies, therefore, IoT technologies are often called mobile IoT.

2.5.2 Smart City

The concept of a smart city originates from the idea of a "smart planet" proposed by IBM. All the smart capabilities of cities depend on a large body of data that is collected by the associated information collector and then exchanged and distribute to different smart city applications for the particular services that designed to process the data or provide information for the demands of its citizens [83].

Fig. 2-1 Smart City Components [85] (from Kolios et al., 2015).

On the strength of the smart city concept, there are many smart city projects that have been successfully built in recent years, however, Komninos considered the British “city” of Bletchley Park in 1939 to be the first smart city [84]. The modern smart city is planned to provide intelligent, convenient and flexible services and applications for urban societies, and its components and architecture have been proposed by Gaur et al. in [85]. Fig. 2-1 explains the components of smart cities that implies they are actually the collection of multiple intelligent services and applications. All these intelligent capabilities are achieved by the multi-level Smart City architecture shows in Fig. 2-2. All the raw data is collected by the widely spread mounted sensors, then the collected data are processed by a four level processing procedure, and then passed on to the tailored services and applications.

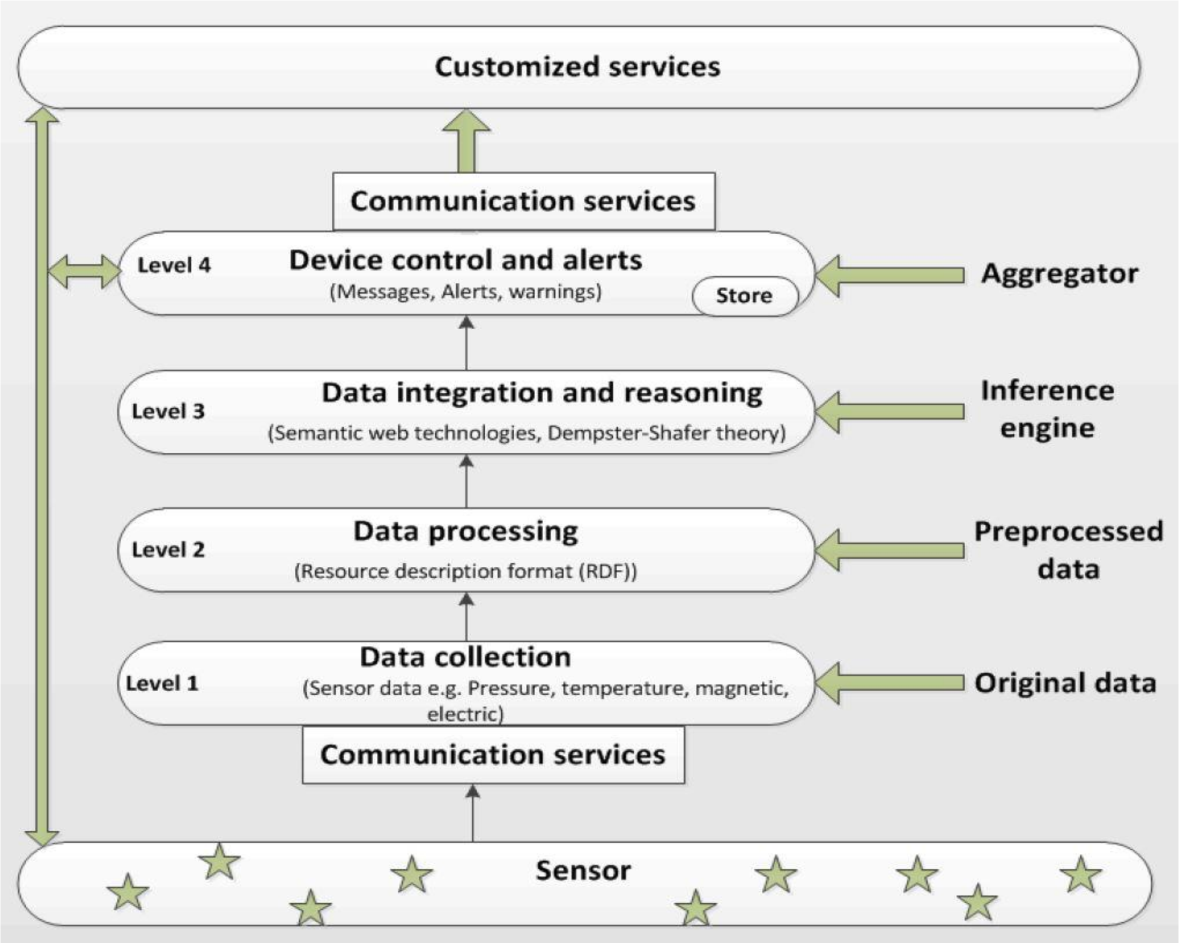

Fig. 2-2 Multi-Level Smart City Architecture [85] (from Kolios et al., 2015).

2.5.3 UAV Assisted Network

Unmanned Aerial Vehicles (UAVs) that are also known as drones, have been widely deployed in wireless communication systems. In particular it is extremely difficult to achieve site acquisition for equipment in high-density areas, so the strengths of UAVs such as flexibility, mobility and adaptive cruising altitude assists the planner of wireless networks achieve fast and cost-effective deployment. Mozaffari et al. give a comprehensive review of applications, challenges and open problems for UAVs in wireless networks in [86] and use Fig. 2-3 to classify different UAVs. Based on the identified characteristics, different types of UAVs are suitable for different application scenarios. In this thesis, there is no particular UAV that will be specified in any scenarios or applications. For the further research, Fig. 2-3 could be a reference for UAV model selection.

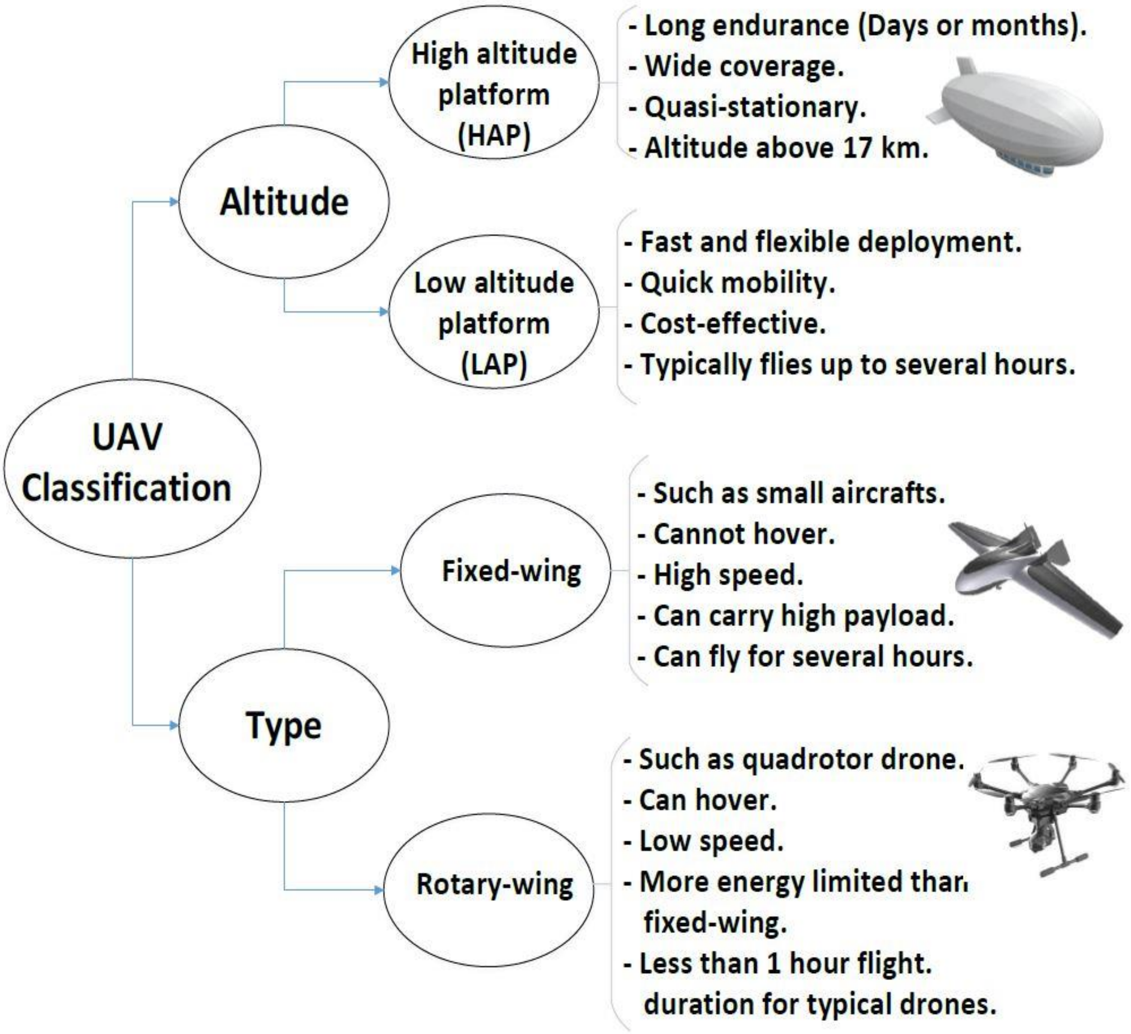

Fig. 2-3 UAV Classification [86] (from Mozaffari et al., 2018).

Zeng et al. expound the basic networking architecture of UAV-assisted wireless communications in [87]. Fig. 2-4 is a basic networking architecture of a UAV-assisted wireless communication system, in which the secondary CNPC links via satellite are an option that provides backup to enhance reliability and robustness. The data links between different UAVs and between UAV and ground terminals are the main stream of the data flow.

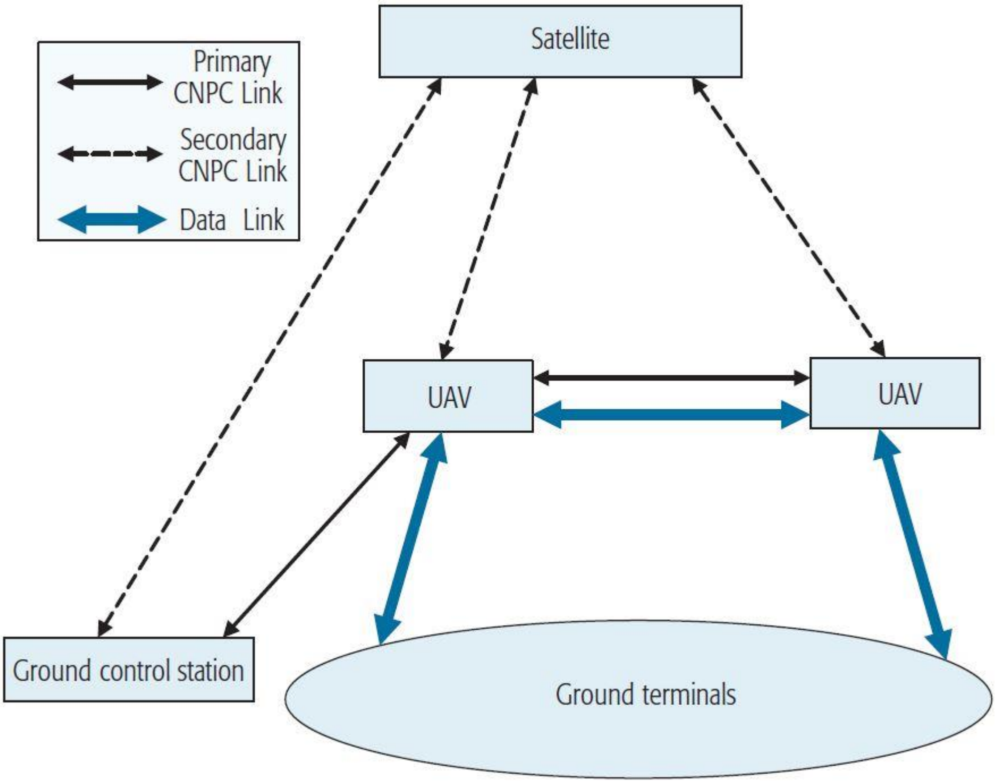

Fig. 2-4 Basic networking architecture of UAV-aided wireless communications [87] (from Zeng et al., 2016).

2.5.4 Applied Devices

There are mainly two issues for widespread use of complex wireless routing algorithms: one is limited resources, capacity and capability on the portable terminals, and the other is the unit cost of smart devices.

As there has been a remarkable development of smart devices, mobile terminals are furnished with a large capacity of memory, storage and batteries. In addition, their powerful processors with multiple cores make possible the implementation of rigorous wireless routing protocols on the serving terminals that endows the device intelligent capability to achieve its smart features.

Mobile IoT technologies and smart city applications and services can share the same platform with other programs, therefore, there is no need to develop a dedicated the platform or software for a particular application. As the technologies gain economies of scale and mass production, the cost of the majority of components and modules in smart gadgets are only a few dollars [88], which makes the unit cost of each smart device reasonable for wide deployment.

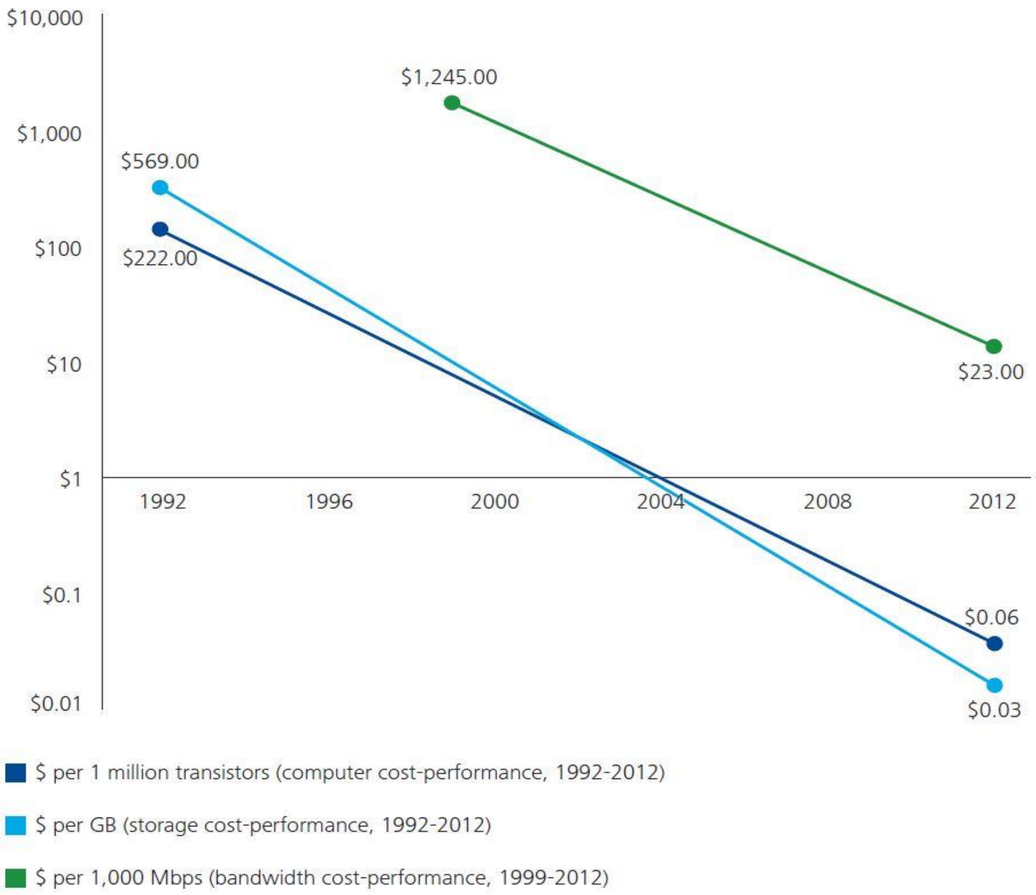

Fig. 2-5 Computing, Storage, and bandwidth cost-performance [89] (from Deloitte, 2015).

A Deloitte analysis report [89] shows that computing power, data storage, network connectivity, miniaturized hardware, and advanced software have an exponential technological progress. Thus, Fig. 2-5 illustrates the cost-performance of the core technologies of computing power, data storage and bandwidth.

2.5.5 Application Integration and Technology Fusion

The fusion of multiple cutting edge of technologies and the integration of emerging applications is inevitable with the hopeful result of the extraction of the strength of the various techniques so that the integration can maximize the advantages of each technology.

Talari et al. [90] give a glance at the concept of smart cities based on the IoT system. Fig. 2-6 displays applications of the IoT system for smart cities, meanwhile, the challenges could be faced for the implementation of IoT-based smart cities are demonstrated in Fig. 2-7. The intelligence of smart cities is reflected by the experiences of its citizens. Applications are the interface between serving entities and served customers. All the challenges could be a part of customer tastes, despite these being good or bad.

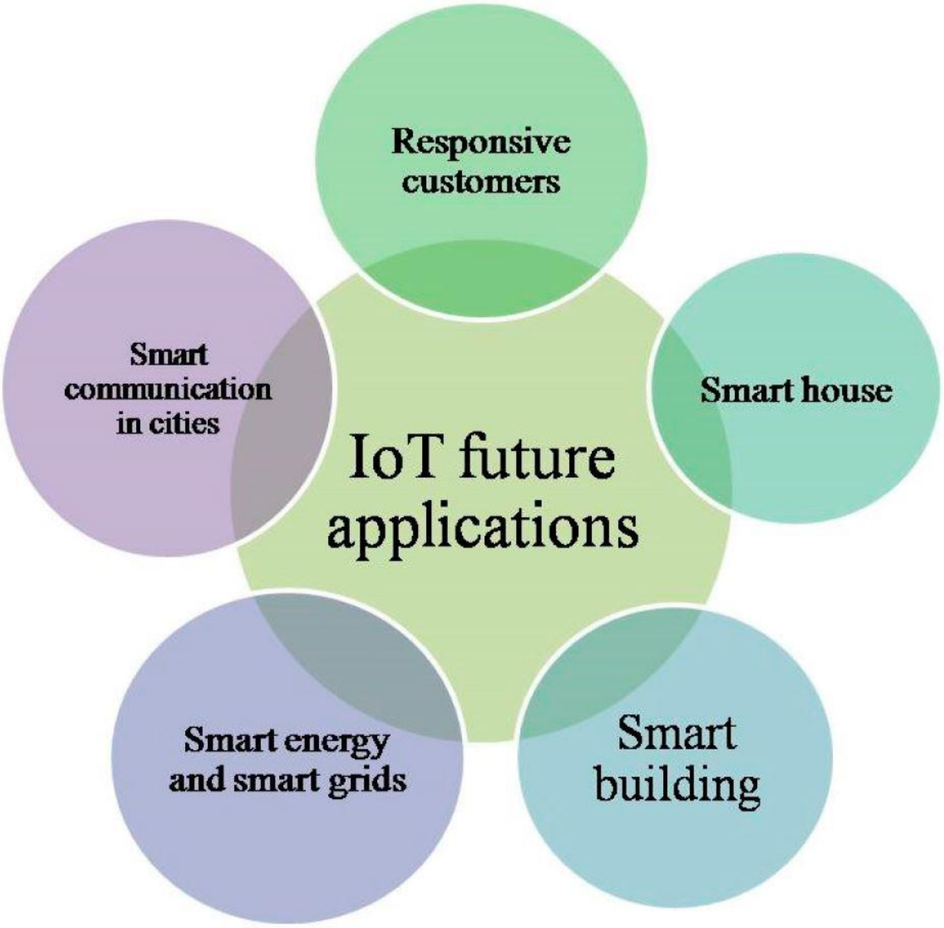

Fig. 2-6 IoT applications for the smart cities [90] (from Talari et al., 2017).

In [91], Suzuki presents a review of the IoT technologies for smart cities, and the further technical evolution. Dustdar et al. [92] give a comprehensive overview of contemporary developments of smart city and IoT research, and the road map of future technologies, which also integrates the social computing and cloud system techniques.

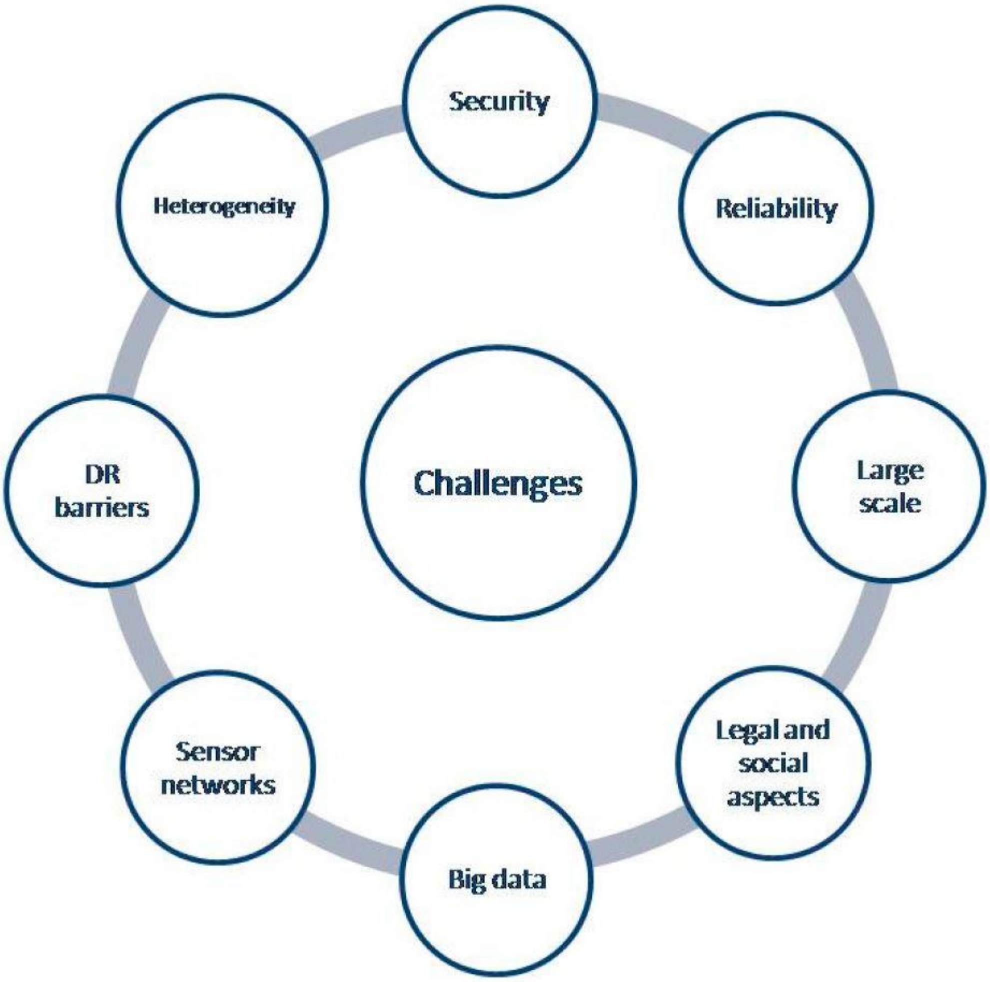

Fig. 2-7 IoT challenges for smart cities [90] (from Talari et al., 2017).

2.6 Summary

This chapter provides a review of the literature regarding the main subject areas related to this thesis. Firstly, a comparison between two concepts of decentralized wireless networks is given and followed with an explanation of the reasons for selecting the DTN as the proposed plan. Secondly, different DTN routing schemes and existing relaying protocols are discussed. Thirdly, the prediction techniques for object movement are described. As technology fusion is in the mainstream of technologies development and evolution, there are many cutting edge technologies and applications that were explored and the DTN relaying scheme identified will be the key approach. The integrated solutions regarding the challenges and issues have been addressed in the first chapter will be proposed in the following chapters.

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Chapter 3

Protocol Design and Simulation

3.1 Introduction

For a closed project design loop, theoretical analysis and design, and a practical testing process are the essential parts of the complete research work. Issues, characteristics and challenges of decentralized wireless network and applied services and applications [1] [2] have been carefully revealed in the first chapter. The principles of DTN routing protocol design and the simulation process are under scrutiny in this chapter. The simulation tool implemented in this project is also introduced.

The work described in this chapter is a part of the entire verification and validation procedure [3], which is for designing software or protocols for communication systems [4], also known as the communication protocol engineering [5].

3.2 Design Conditions

Although the DTN system has undergone great evolution since its original conception, the essence and basic network structure [6] is still the same. That is, portable nodes in the network use the encounter opportunity of different mobile devices to realize the delivery of messages, to achieve an acceptable network performance in various seminars when the network is experiencing lack of resources or the communication environment is bad.

Because of the characteristics of decentralized mobile systems and the issues and challenges that have been revealed in Chapter 1, the following conditions have to be considered during the design of DTN routing protocols:

- Availability and limitations of system resources
- Dynamic network topology and radio coverage
- Network throughput to keep an acceptable and stable level
- Vulnerability and unreliability of mobile terminals
- Suitable and feasible security mechanisms

3.3 Design Principle

Routing protocol design is an essential work element of DTN networking research. The routing design problem of DTN networks has different constraints and scope than conventional centralized wireless networks and operated mobile systems. This can be easily seen via the differences in issues and challenges between these systems that have been revealed in Chapter 1. An excellent DTN routing algorithm can ensure that data packages are transmitted at a minimized cost and time delay. The transmission cost is the total amount of usage of network for delivering a message from the source node to the destination node.

The transmission cost can be measured by various criteria and concerns based on the network design purposes that include: hop count, transmission energy cost or overall cost, transmission latency, physical path distance and weighted distance. The route change and hop selection can be determined by neighbouring node comparison, history of encounters and prediction outcomes. The existing DTN routing protocols that have been reviewed in section 2.3 all use these schemes. For example, PRoPHET is one of routing protocols that typically applies history of encounters and LPFR-MC is based on the prediction outcomes. In [7], Cao and Sun compared routing strategy design for different DTN algorithms.

The quality of design of DTN relaying protocols can be assessed by using the following aspects:

- Adjustable parameter for controlling route updating to apply the protocol in different applications avoid the occurrence of unnecessary relaying, and to free radio bandwidth with resultant reduced portable terminal energy consumption.
- Adjustable parameter for changing the algorithm’s computational complexity and adapting the routing algorithm onto different portable devices.
- Scalability for different network populations, coverage territory, traffic load and applications and services.

The DTN routing protocols proposed in this thesis use movement prediction outcomes to determine the data message routing path and to find the best route with the smallest hop count, transmission cost and transmission delay. The designed relaying algorithms provide some adjustable parameters to adapt the protocol into different application scenarios. Their considerable compatibility lets the protocols be deployed in a wide range of decentralized wireless network conditions. A detailed introduction to these features will provided in the following chapters.

3.4 Routing Strategy

Decentralized mobile systems lack continuous complete end to end radio connectivity and there is no centralized management mechanism available to control the system information distribution; all mobile service subscribers form the wireless network autonomously and voluntarily. As the requirements of delay tolerance have to be met, each intermediate relay node has to buffer the transmitted data packets and wait until the appropriate relaying node towards the destination appears. The method to determine the next best data packet hop among different availabilities is critical to raising the overall system performance of mobile DTNs.

3.4.1 Determination Method

When a source mobile node generates a message or an intermediate node stores and carries a relayed data packet, this node starts observing the movement of adjacent portable devices which can establish a bi-directional air link to relay the data packets. The observed movement data are seen as the mobile subscriber state at the moment when the observation takes place. These measurement data form the prior information for the KF algorithm reasoning inputs to predict the movement state of mobile users in the next instant. Based on these prediction data, the observing node will have the transmission probability of the targeted node moving towards the destination to achieve delivery. After the observing node repeats the same observation and prediction process for each adjacent observable mobile subscriber, it will have a complete list of transmission probabilities for all adjacent portable nodes. All the serving nodes in the wireless network exchange the transmission probabilities, then each mobile node can work out the transmission probability to the destination. The message source nodes or the store and carry intermediate nodes forward the packet to the node that has the highest transmission probability on the relaying path toward the destination.

As an option, for a certain management purpose of the DTN network, a designed predefined threshold n could be set for the transmission probability to pause the forwarding process when there is no appropriate intermediate wireless node available, to avoid the occurrence of unnecessary relaying, and to free radio bandwidth with resultant reduced portable terminal energy consumption. The design principle of a transmission threshold is to help the mobile network designer meet various system performance targets regarding different factors, for instance, delivery rate, average latency, hop count and energy consumption of relaying. For example, a higher threshold can ensure that the packet is forwarded to a more reliable relaying node. This does, however, cause the data packet store and carry node to wait longer for a suitable hop, potentially increasing average latency. The advantage of the threshold is a reduction in the hop count and energy consumption for relaying. Nevertheless, the predefined threshold cannot be very high as in some circumstances high transmission probability relaying nodes may rarely appear. So the configuration of the predefined threshold needs to be based on the network condition and designed performance targets of the specific mobile system.

3.4.2 Forwarding Strategies

The KF routing strategy proposed in this thesis is a single copy routing scheme, in which only one copy of a message will be forwarded in the wireless network, this differs from multiple copy routing protocols that relay a message to multiple mobile nodes to increase the overall delivery probability.

There are some metrics to select the best route in dynamic routing to forward the packets: hop count, bandwidth, path load, time delay, energy consumption or expense costs, encounter history and movement prediction. Some routing protocols that have been introduced in Chapter 2 are encounter history based, PRoPHET is the classic example and one of the earliest using the history of encounters. FGAR and SEBAR extend the meaning of the history of encounters in some terms.

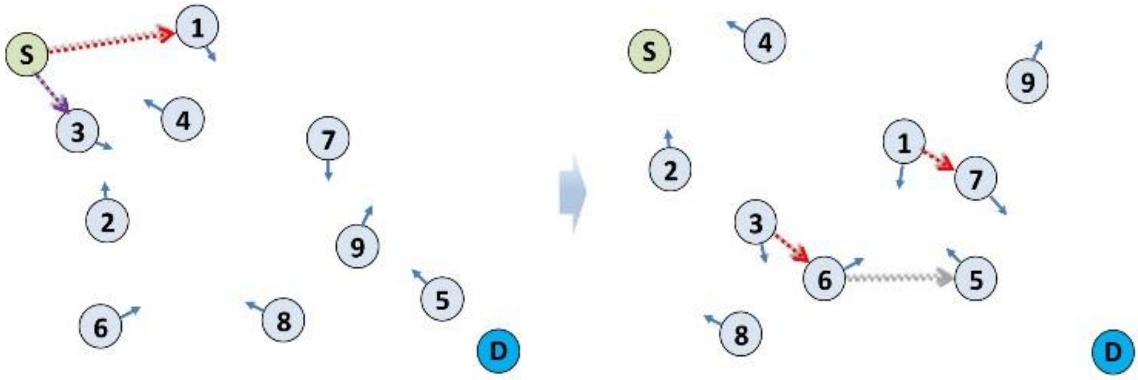


Fig. 3-1 Portable nodes movement evolution diagram.

Fig. 3-1 gives an example of the movement evolution of nodes; on the left of the figure is shown the position of each node in a DTN, and on the right new node positions in the next moment. Here it is supposed that the source node S and destination node D are steady, and all the rest nodes are moving around the radio serving area. Fig. 3-2 and Fig. 3-3 illustrate the relaying paths for different forwarding strategies of single copy routing schemes based on different forwarding metrics.

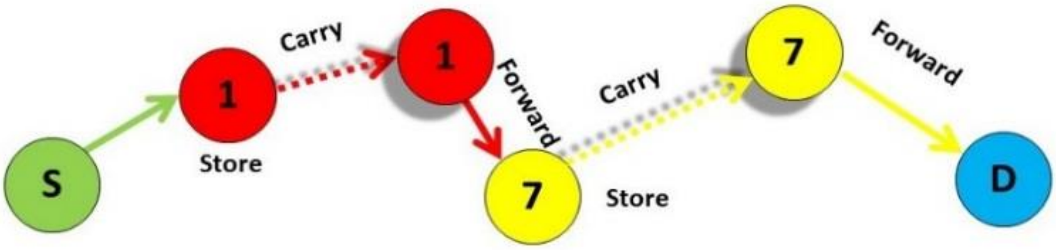


Fig. 3-2 Relaying path for movement prediction based routing protocols.

Fig. 3-2 shows that the movement prediction based routing protocol is able to find the nodes among candidate devices that are more likely to be moving towards the destination node, and forward the data packet efficiently. In contrast, the encounter history based routing protocols could forward the packet to a node that carries the message in an unhelpful direction. As Fig. 3-3 shows, the data packet could suffer a longer delay or end up with the high encounter history node 5 (moving in the wrong direction) as this node has just left the destination node D.

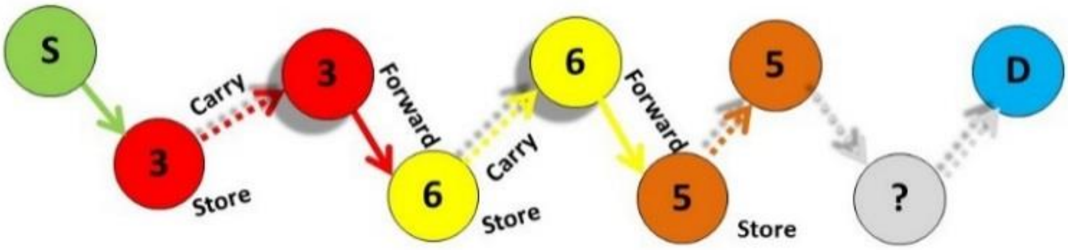


Fig. 3-3 Relaying path for history of encounters based routing protocols.

As Fig. 3-2 and Fig. 3-3 illustrate, the optimized relaying route reduces hop count and thus the total energy cost for portable devices to emit message signals. Recalling Fig. 3-1, it can be seen that a movement prediction strategy reveals the shortest message relaying path and provides the smallest delivery latency, which helps mobile DTN systems increase their overall efficiency.

For the movement prediction based routing strategy, the prediction algorithm uses the current movement states (location, velocity and acceleration) to predict the motion of targeted wireless nodes, and to infer their movement trends. It then determines the message relay action to minimize the message flood, reduce the transmission energy consumption and save the radio bandwidth between nodes. The KF and PF are algorithms that use the recursive update process to estimate the state of targeted moving objects. The KF method achieves this goal using Gaussian estimation, while the PF algorithm accomplishes this by a sequential Monto Carlo method. As the KF and PF applied in this work are recursive estimation algorithms, in each next step the posterior in the last step will be the prior input for the prediction calculation; the applied prediction algorithm does not need memory to store the trajectory history.

For the KF based routing protocol, the algorithm itself is rather simple in terms of processing and does not require substantial computing power, the detailed information will be given in Chapter 4.

For the PF based relaying strategy, as the network elements embedded diversified available processing resources such as, processing capacity, memory size and battery capacity. The adjustable number of particles lets the proposed routing protocol be accommodated by any portable terminals easily, this part will be described in the protocol design of PF in Chapter 6.

3.5 Simulations

After the design work of proposed routing protocols has been completed, it needs to be tested in appropriate simulated environments to verify whether the protocol designed satisfies specified requirements. In this PhD work, there is a list of demands that needs to be considered to evaluate the design.

- *Functionality*: to the best of the author’s knowledge this work is one of the first studies on adopting filtering technologies, in use of movement tracking to assist the DTN routing determination, therefore, the first task is to check whether the proposed protocol can achieve the basic function to deliver data packages from the source to its destination.

- *Adaptability*: due to the complexity of the situations in which DTN is applied, such as the constant changing of node locations, radio links, network topology, population of portable nodes and data traffic, the protocol needs to be adaptive for different scenarios.

- *Performance* refers to the measurable outputs to facilitate a quantitative analysis [8] regarding multiple key indices. A well-designed relaying protocol shall be able to deliver a good and stable performance regardless of the change of mobile network conditions and other factors. In particular, when estimating different DTN routing protocols, the comparison shall be a comprehensive estimation across multiple metrics.

Based on the requirements listed above, the simulation tool selected is required to provide the function to accomplish all the simulation process and output measurable and quantifiable simulation results, thus, the testing procedure needs a dedicated and powerful DTN simulation tool.

3.5.1 Simulation Tool

Although there are some existing communication network simulation tools, such as NS-1 [9], NS-2 [10], NS-3 [11] and OMNeT++ [12], they are all discrete-event computer network simulators, which lack good support for the DTN system environment. DTNSim [13] and DTNSim2 [14] are the simulation tools for the DTN environment, however, they solely focus on routing simulation, and the first released version does not support most of classical DTN routing algorithms. The subsequent releases have less technical evolution for the later version of DTN routing protocols.

A good network simulation tool should be able to simulate the substantial functions of routing algorithms, data generation and communication protocol events such as the establishment or interruption of connections between nodes. Although pseudo random number generators can be used to create the data, it is a great advantage to be able to take communications log data, such as node information, contact duration, location, etc. through portable devices, from real life projects as input. There are some online resources collect these data can be implemented as real world trace into the DTN routing simulation, which can be downloaded from the CRAWDAD [15] (A Community Resource for Archiving Wireless Data At Dartmouth) (http://crawdad.cs.dartmouth.edu/) repository is an archive of wireless network data resources for research purpose activities. CRAWDAD archives real world wireless trace data from many contributing locations. There are large number of publications using the trace records collected by CRAWDAD to improve experimental model, for instance Huynh and Radenkovic from the University of Nottingham developed a cross-layer framework for large scale emergency communications [16] used the GPS trace data collected by Cabrero et al. when they studied on Opportunistic Networking for Emergency Services [17]. These data are also partially used in this PhD work to simulate the movement as the real trajectory of moving objects. In [18], Hui et al. introduced the methods to test and evaluate their own designed forwarding algorithm using multiple experimental data sets. Actually, all these data sets were subsequently collected by CRAWDAD afterwards.

In this thesis, the proposed DTN routing protocols will be simulated and evaluated by the opportunistic network environment (ONE) simulator [19] [20] that was developed by Keranen and Ott in the University of Helsinki, Finland. The software is a Java-based open source discrete event simulation engine for simulating the sending and receiving of DTN messages by using different routing protocols, and generates a record of the movement trajectory in a DTN network environment, and is an object-oriented and event-driven simulator. The ONE simulator can simulate the real network environments by load in the collected objects moving records. It has the following features:

- Generation of node move events based on different movement models.
- Five different movement models:
    - Random WayPoint (RWP)
    - Map Based Model (MBM)
    - Shortest Path Map Based movement Model (SPMBM)
    - Route Based Model (RBM)
    - External mobility model
- Loading of real world trace records as the movement data to implement the routing protocol simulation.
- Display of messages between various DTN routing algorithms, sender and receiver type nodes.
- Real-time graphical display of node movements and messages by provided GUI (Graphical User Interface) to present the real time movement of mobile

nodes, and the message transmission process between different relaying hops then illustrate the message forwarding path.

- The results can be visualized using the graphical tool to generate the different format of outputs.
- The opportunity for researchers to develop their own routing model and complete the simulation process.
- Two different ways to import events, and the ONE simulator can support both event generation methods at the same time:
    - External events file: it is a document in txt format that records time stamps of events.
    - Message event generator: it is a Java class that generates events dynamically.

Fig. 3-4 shows the structure of the ONE simulator [21]. The simulation environment consists of movement models, route models, event generators, and visualization and results models. In which, the movement models command the behaviours of mobile node during the simulation process that is a map-based movement or input from files. The external trace could be the data collected by CRAWDAD project. The routing simulation model is the core part of the ONE simulator that determines how the nodes discover the next hop or destination and relay the message. The report module can collect data of simulation and output either in numerical or graphical forms.

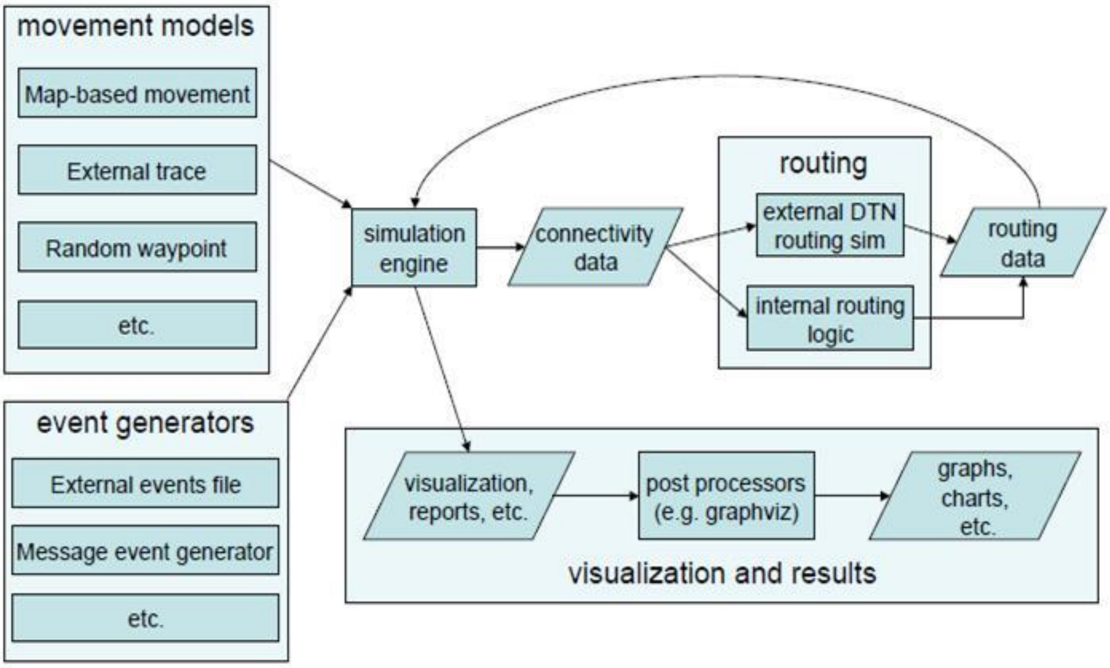


Fig. 3-4 Structure of the ONE simulation environment [21] (from Keränen et al., 2009).

Fig. 3-5 displays the software packages and data flow of the ONE simulator [22]. In the core package, the core components contain the classes representing a DTN host or a link. The GUI part is in the graphical display package that has the playfield sub-package involves classes presenting graphical objects. The report block collects outcomes routing and movement modules to generate multiple simulation reports, which can be setup in a setting document.

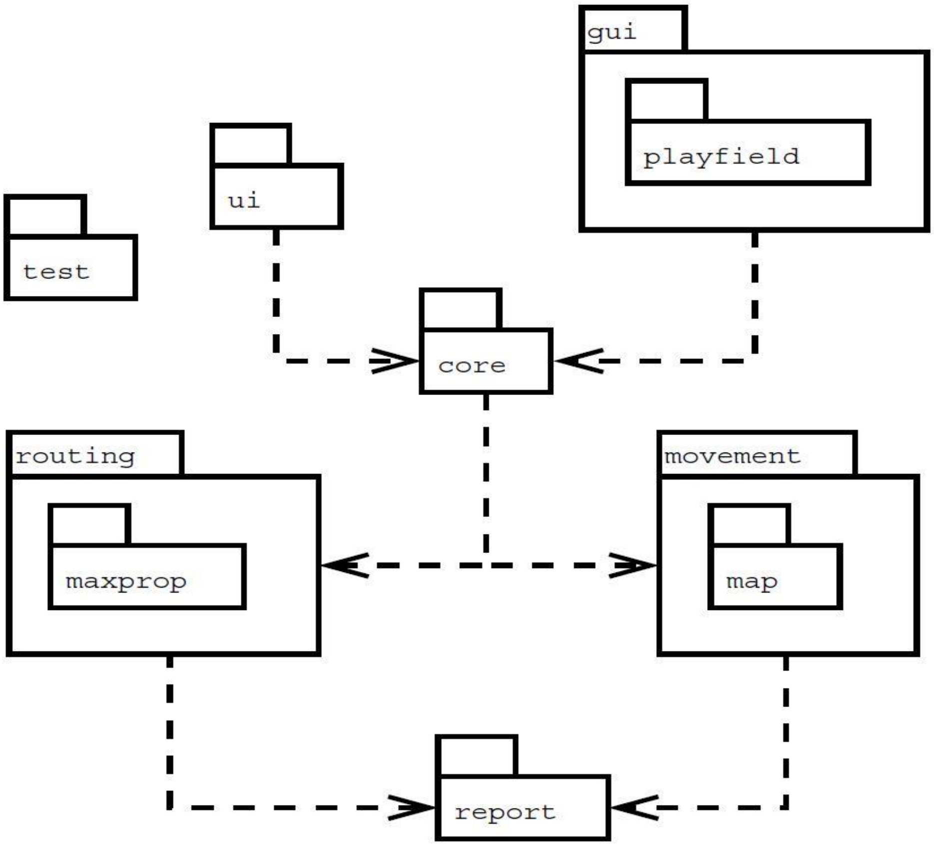
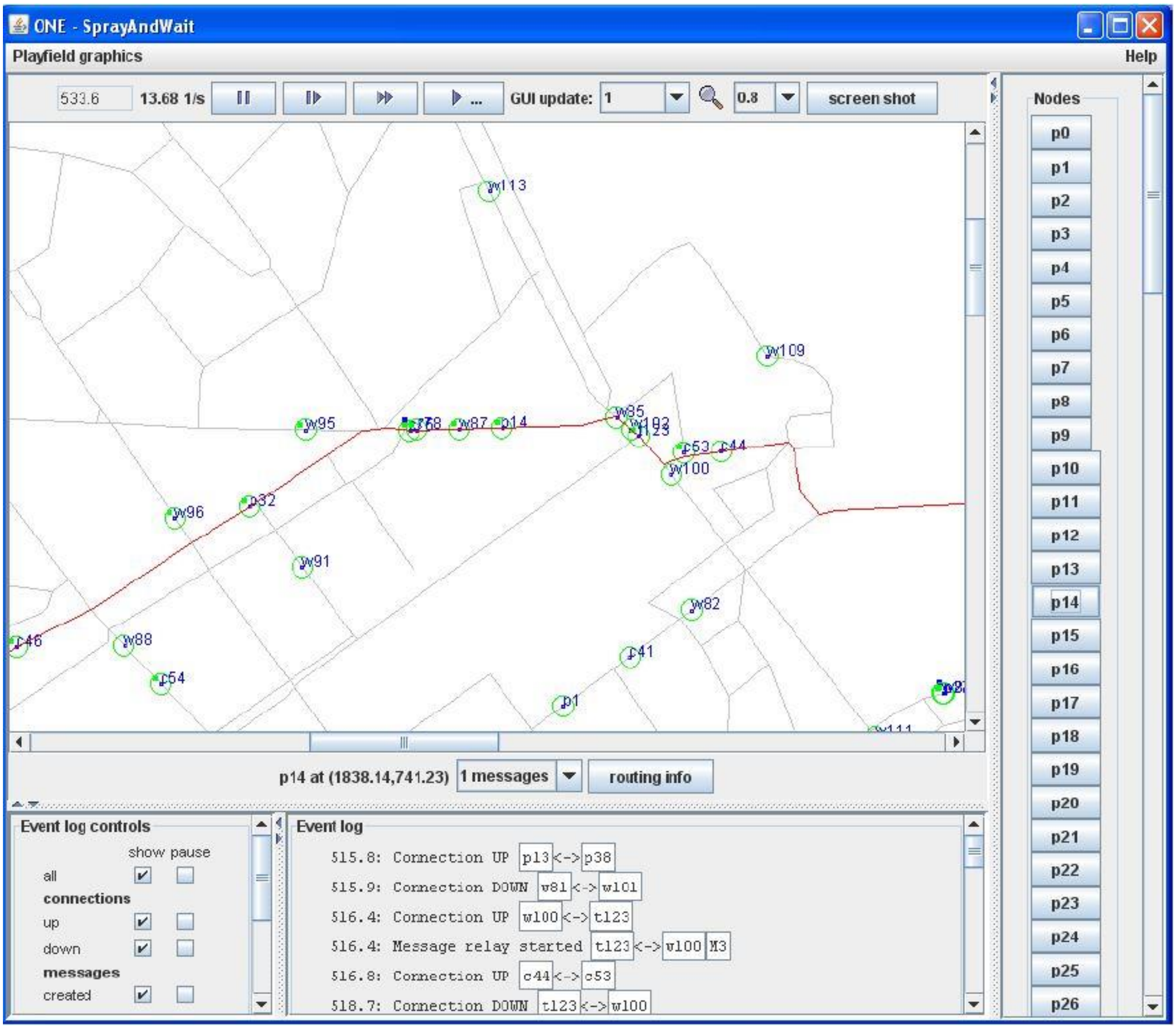


Fig. 3-5 The ONE software packages [22] (from Keränen, 2008).

The ONE simulator can be operated in two different methods: GUI mode and batch mode. Fig. 3-6 is a screen capture of the GUI mode [22]. The main part of the screen is Playfield graphics in gui module that displays a part of the geographical simulation area. The map can be zoomed in and zoomed out by changing the display scale. The narrow panel on the right of the screen lists all the nodes in the simulation network. Clicking the number of a node can track each individual node. The event log panel shows the instant event between different moving nodes. The user can select multiple options in the event log controls panel to change the events as shown in the event log and main simulation window.

If the simulation needs to run with multiple setting of parameters, the ONE simulator provides the batch mode which runs the program more efficient as it has no real-time visualization. The majority of the simulation work in this thesis was completed in the batch mode. For a certain simulation scenario, all the settings are setup in a configuration file that includes various parameters. The key estimation parameters are selected for this PhD work will be described in Section 3.5.3.2.



p14 at (1838.14,741.23)

Event log controls

	show	pause
all	☑	☐
connections		
up	☑	☐
down	☑	☐
messages		
created	☑	☐

```
515.8: Connection UP p13<->p38
515.9: Connection DOWN w81<->w101
516.4: Connection UP w100<->t123
516.4: Message relay started t123<->w100 M3
516.8: Connection UP c44<->c53
518.7: Connection DOWN t123<->w100
```

Fig. 3-6 The ONE screen shot [22] (from Keränen, 2008).

3.5.2 Simulation Source Data

Although the CRAWDAD project provides the database for the collection of real trace data, the public availability of mobile devices movement trajectory records is rather limited. To achieve a comprehensive simulation of routing protocol designed for decentralized mobile systems, two categories of trace data were applied to simulate two kinds of network conditions: a simple wireless network and a complex wireless network.

For the simple mobile network scenario, the trace data was downloaded from the CRAWDAD archive that contains mobility and connectivity traces extracted from GPS traces collected from the regional Fire Department of Asturias, Spain. The original data source was one year of GPS traces extracted from a Geographical Information System (GIS). The traces were generated by GPS devices embedded mainly in cars and trucks, but also in a helicopter and a few personal radios. A total of 229 devices reported 19,462,339 locations. A new location was reported with an interval of approximately 30 seconds when the GPS device detected movement. To convert GPS traces into ONE connectivity traces, the circular communication range was been assumed be 200 metres [17].

For the complex wireless network condition, the simulation used the map-based movement model. The map data was the downtown area of Helsinki city including road and pedestrian walk paths within a terrain of 8300 X 7300 metre. The connectivity traces for the real time location data of various moving objects carrying the mobile device, such as pedestrians, cars and trams, were generated by the simulator [21].

3.5.3 Protocol Estimation

To comprehensively explore the performance of proposed protocols, the routing algorithms need to be tested with multiple configurations of key parameters to simulate different DTN wireless network conditions, demands and applications, regarding system traffic load, number of online subscribers, service and application categories, traffic availability and so on.

3.5.3.1 Evaluation Metrics

Using the ONE simulator, it was possible to investigate the performance of various wireless routing schemes via various metrics. All tests were measured in terms of the following four metrics to evaluate the network performance [23], and also present a comparison with other routing protocols [24]:

1) *Delivery probability* is defined as the average ratio of the total messages received by the destination node to the total messages generated by the source node, which implies the overall achievements of a communication system for delivering data. This is the most important factor to estimate the performance of a DTN since this factor evaluates the essential capacity of the routing protocol for delivering the data packets to its destinations and a stable delivery probability shows the robustness and resilience of the DTN relaying protocol.

$$Delivery\ Probability = \frac{Number\ of\ messages\ received\ by\ destination}{Number\ of\ messages\ generated\ by\ source}$$

2) *Overhead Ratio* is defined as the ratio of the number of redundant messages and the number message delivered to the destination expressed as a percentage. This metric evaluates the efficiency of a routing scheme in process messages because a lower

overhead ratio means less resources expended in messages that do no convey information content. A high overhead ratio means a large number of packet replicas could flood the network. An increased message collision probability will consume much more energy for smart terminals. This factor is one of indicators to evaluate mobile nodes energy consumption.

$$Overhead\ Ratio = \frac{Messages\ relayed - Messages\ received\ by\ destination}{Messages\ received\ by\ destination}$$

3) *Average Latency* is average time spent in transit by messages generated by source nodes to messages received by destination nodes. For DTN systems, although transmission latency is acceptable for many applications, too high a value could make some applications not viable. The long delay also could cause the carrying mobile nodes to exceed their maximum buffer space and make some nodes become unavailable for relaying packets. A small transmission delay means that the routing algorithm has strong transmission capability and high transmission efficiency, and fewer network resources are required in the packet forwarding process.

$$Average\ Latency = \frac{Total\ delivery\ time\ duration}{Total\ Messages\ received\ by\ destination}$$

4) *Average Hop Count* is the average number of hops for the received messages between source nodes and destination nodes. As can be seen in Fig. 3-2 and Fig. 3-3, the optimized route can not only shorten the relaying path but also reduce the hop count and delivery time. As each transmission costs energy to emit the signal between nodes, a reduced average hop count can save mobile terminal energy. This factor is one of main indicators to estimate the system efficiency and overall energy consumption regarding the data transmission.

$$Average\ hops\ count = \frac{Total\ delivery\ hops\ count}{Total\ Messages\ received\ by\ destination}$$

The routing protocol performance is not suitable for assessment by only a single evaluation metric, for example, the relaying strategy may use a long delay to maximize the delivery probability as delivery ratio is the key measurement of network performance. For a certain design purpose or application or scenario, a multiple index comprehensive evaluation method can be designed which includes different measurement weights for each aspect. The measurement weights can be adjusted to have different evaluation combinations regarding different applications.

3.5.3.2 Estimation Parameters

The ONE simulator provides multiple parameters that can be setup in its configuration file: Scenario update interval, simulation during, scenario end time, wireless interface type, transmission speed, transmission range, movement model, number of hosts, buffer size, waiting time, moving speed, message time to live and so on. To simulate different scenarios of the wireless network conditions, the following parameters were applied in the simulation for the proposed routing protocols and existing protocols:

1) *Number of hosts Mobile Node*: This parameter simulates the different densities of the population of wireless devices attach to the proposed system, for instance, when portable nodes are sparse, there is less opportunity to deliver the message from source node to its destination, and some edge mobile subscribers could be unreachable. In this case, the delivery probability is nil for this network element, however, if a well-designed routing protocol has solution to tackle on this scenario, the delivery rate can still keep at an acceptable level. In contrast, by the increase of mobile devices, the DTN system becomes dense or high dense network, some network members could also be isolated due to heavy traffic blocking air links connected to adjacent nodes. Especially for the decentralized wireless system, this could be a big potential issue and cause a widely spreading traffic block, which then causes the system to collapse. The DTN relaying algorithm design needs to consider the extreme conditions to avoid the system failure.

2) *Buffer size*: The configuration of buffer size assumes the memory size on each mobile node that dedicated for the DTN routing protocol to buffer the intermediate data packages. When the cache is full, the node will not receive any messages until some old messages are discarded. The buffer size cannot be setup with a large value, since there are various portable devices are involved in the mobile network, especially some low cost equipment does not have big embedded memory. A large amount of buffered data can affect the operation of its designed functions.

3) *Message size*: Message size gives the range of size of each message segment. For packet switching, large messages will be cut into small segments and encapsulated into data packages. The network protocol delivers data packages from source to its

destination individually, which could be routed through different path. After the destination node has received all of data packages, it extracts the payload and assembles all the information segments into the original message.

4) *Message Time To Live (TTL)[25]*: This parameter defines the maximum lifespan or lifetime of data messages in the DTN mobile network. The units of TTL are normally seconds, but in the ONE simulator the TTL is counted in minutes. TTL could be setup over a large range of values, shorter TTLs can keep relayed messages fresh, however, given the nature of DTN systems, the delayed data needs to be tolerable for an unpredictable delay. A large number of data packages will be abandoned from the intermediate nodes if the TTL is insufficient, which causes a high drop rate and low delivery probability. A large value of TTL could be helpful for the delivery probability as the intermediate nodes gain more opportunities to forward the data to the destination nodes. The problem is that the undeliverable data occupies a vast amount of resources causing a low efficiency of the DTN system. To test and find an appropriate value of TTL is an important aspect of the work of DTN design.

5) *Message Interval*: The message interval gives the time period between two generated the messages from source node, which is in inverse proportion to the message generation rate. This parameter simulates the data traffic load, and the units are seconds.

The different combination of parameters can simulate different scenarios and applications in the network, such as the pair of message size and message interval, small message size and message interval could imply social networking applications, for instance WhatsApp, Twitter, Messenger, and location or state updating, positioning etc. On the contrary, large message size and message interval could be services like downloading, streaming, FTP, and so on [26].

3.5.4 Simulation Configuration

In the ONE simulator, there are multiple parameters can be setup to simulator various complex application scenarios, for instance Barzan et al. simulate some extreme conditions, music festivals or other mass events which cause an extremely high density of mobile devices and significant traffic volumes, to test and compare some well-known opportunistic routing protocols [27].

To gain significant insight into the routing protocols designed, a range of different scenarios need to be simulated and tested, and a series of analysis and comparisons were performed as will be detailed in subsequent chapters. Table 3-1 lists the defined values or particular ranges for the selected key parameters which have been described in Section 3.5.3.2. For different simulation purposes, the combination of these parameters could be different.

TABLE 3-1 PARAMETERS OF SIMULATION CONFIGURATIONS

	Label on the graphs	**Value of parameters**
Dimension		8300 X 7300
Buffer Size	B	10, 20 MB
Message TTL	T	30 minutes
Message Interval	I	1, 5 seconds
Message Size	M	0.3-0.5, 0.5-1.0, 1.5-2.0, 2.5-3.0, 3.5-4.0, 4.5-5.0, 5.5-6.0, 6.5-7.0 MB
Number of Nodes	H	50, 75, 100, 160, 200 (only for simple network)
Simulation Time		86400 Seconds
Transmit Range		20 – 1500 metres
Transmit Speed		250 kBps – 10 MBps
Protocol		Kalman Filter (KaFiR), Epidemic, Direct Delivery, Spray and Wait (Binary version), Spray and Focus

3.6 Summary

This chapter has provided a disciplinary overview of protocol design principles and simulation processes that are of interest to this thesis. The routing strategy includes intermediate node determination methods and data packet forwarding strategies that are the core of decentralized wireless protocol design and substantial contributory parts to the system performance. Then a simulator tool has been introduced to test the performance of the protocols designed, and some key metrics and estimation parameters presented to complete the analysis.

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Chapter 4

KaFiR --- Kalman Filter Routing Scheme

4.1 The KaFiR Routing Protocol

The wireless DTN system benefits from the mobility and flexibility of mobile subscribers, however, it brings many uncertainties into the wireless network. Some existing routing schemes introduced in Chapter 2 attempt to minimize the nature of DTN uncertainty using different strategies. Study of movement prediction of the mobile users is a method to control these uncertainties comprising a series of estimations of moving targets. This can use techniques from problems in different areas such as tracking flying objects using radar. Tracking is a special case of estimation, in which the inference of mobile subscriber movement will be represented as a set of complex state space estimation elements [1], each of which records a certain mobile subscriber's position, instantaneous velocity and instantaneous acceleration (or deceleration).

For each particular moment or interval, every individual mobile node will have its own set of state data to indicate its state space information in a state space model. This set of data will be denoted as a vector of the state space identification. A series of state vectors is used to record the trajectory of a particular mobile subscriber or a predetermined mobile user group within the network.

All mobile nodes have the ability to move around the radio frequency coverage area freely, and this random motion is a category of stochastic system. In particular, this is in mathematical or statistical terms a random walk [2] of subscribers described via a stochastic process [3]. The unknown state of the targeted wireless subscriber (denoted by X) is computable by the appropriate mathematical and statistical theories based on the observation or measurement data of behaviour of the particular mobile subscriber (denoted by Y). For further movement, mathematical and statistical methods can also assist the production of an inference result using historical measurements [4].

Here, established Bayesian statistical methods are used to accomplish the moving object motion prediction operation [5]. According to the overall behaviour of mobile subscribers, the nodes will be classified into different categories by utilizing different criteria, for instance, non-maneuvering objects and maneuvering objects. If the objects are maintaining a constant velocity so that they may be classified as the non-maneuvering type, then the system can be defined as a Linear Quadratic Gaussian (LQG) one [4]. Such a system belongs to a framework of circumstances which contains the fundamental tools of stochastic optimal control, and the tracking, filtering, smoothing and prediction operations can be solved using linear system models. The motion of maneuvering objects is normally more dynamic with different accelerations and the trajectory is nonlinear so the solution will be found under more complicated circumstances which could be such that only sub-optimal solutions are achievable [6]. Each mobile node only needs to track and predict the nodes with which it is able to establish a direct bi-directional radio connection and the prediction information is only exchanged among these neighbouring mobile nodes. To achieve this prediction, each mobile node needs to track and obtain the state information for all of its neighbouring nodes by observing and tracking their movement. The routing decision making process is shown in Fig. 4-1.

4.2 Tracking Strategies

The tracking problem is actually to estimate the state of moving targets based on the observation data via statistical algorithms. The state of the targets can thus be seen as belonging to a dynamical system [7] and the states are independent of the time, forming an autonomous system. The motions (or trajectories) of targeted mobile subscribers are normally continuous, but the observers take the observation data in each constant time interval or according to a preset fixed sampling frequency, making the observations discrete. This mathematical statistics mode is called the continuous – discrete filtering mode [1], and the observation results are in the discrete mode that will be the state space information input. The movement of mobile users cannot remain at a constant velocity or absolute steady state. In practice, small changes in the velocity or state close to the mean value may be treated as Gaussian noise.

The classical Bayesian approach provides a method to deduce the further states of observed moving objects. Bayes' theorem [5] implies that the mobile node states can be predicted from the observation data, which is the joint probability of the state of event x and the observation of event y divided by the unconditional probability of the observation of event y, which is the normalization factor.

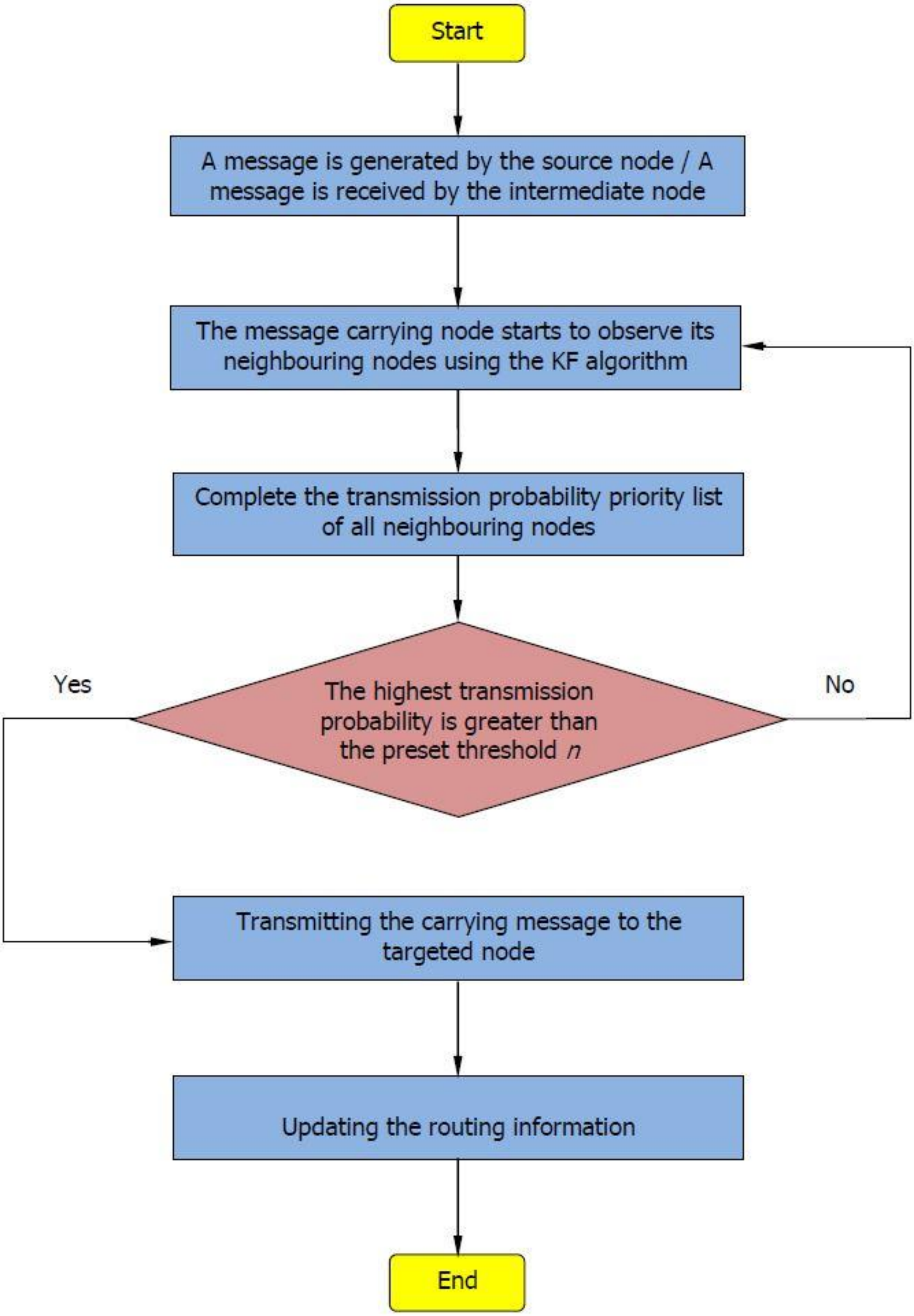


Fig. 4-1 Flowchart of the routing decision making.

The movement of a mobile subscriber is a random walk [4] obeying the Markov property [8], so the stochastic motion of each mobile node can be treated as a series of Markov process individually. A first order Markov chain can be used for predicting the state space identification of each mobile subscriber step by step. The recursive Bayesian solution is [8]:

$$p(\boldsymbol{x}^k|\boldsymbol{y}^k) = \frac{p(\boldsymbol{y}_k|\boldsymbol{x}_k)}{p(\boldsymbol{y}_k|\boldsymbol{y}^{k-1})} p(\boldsymbol{x}_k|\boldsymbol{x}_{k-1}) p(\boldsymbol{x}^{k-1}|\boldsymbol{y}^{k-1}) \qquad (4-1)$$

leading to a state conditional density:

$$p(\boldsymbol{x}_k|\boldsymbol{y}^k) = \int_{\boldsymbol{x}_{k-1}} p(\boldsymbol{x}^k|\boldsymbol{y}^k) d\boldsymbol{x}_{k-1} \quad . \qquad (4-2)$$

In these equations, the superscripts refer to vectors of all *x* or *y* values from one to *k* or *k-1* whereas the subscripts denote single instances of *x* or *y*.

4.3 Mathematical Model

The targeted system and observation methods are based on linear system models with quadratic system optimization. The wireless system and observation are subject to Gaussian noise so they obey the basic Linear Quadratic Gaussian (LQG) regulator [4]. Hence, the object tracking and movement prediction problem can be solved by a Kalman Filter (KF) [4]. Equation (4-2) is the recursive estimation of the state conditional density function and the term $p(\boldsymbol{x}^{k-1}|\boldsymbol{y}^{k-1})$ gives the prior probability density function. In the Bayesian recursive solution, $p(\boldsymbol{x}_k|\boldsymbol{y}^k)$ is a conditional density of the targeted mobile subscriber state $\boldsymbol{x}_k = (x_{k1}, x_{k2}, \dots, x_{kn}) \in \mathbb{R}^{\mathrm{n}}$ at the moment k given all the observed data $\boldsymbol{y}^k = (\boldsymbol{y}_1, \boldsymbol{y}_2, \dots, \boldsymbol{y}_k)$ with $\boldsymbol{y}_k = (y_{k1}, y_{k2}, \dots, y_{km}) \in \mathbb{R}^{\mathrm{m}}$.

The moving object tracking algorithm with noise is:

$$\boldsymbol{x}_k = \mathrm{f}(\boldsymbol{x}_{k-1}) + \boldsymbol{v}_k \qquad (4-3)$$

where $\mathrm{f}(\boldsymbol{x})$ is some function of $\boldsymbol{x}$ and $\boldsymbol{v}_k$ is a vector of Gaussian noise.

In practice, the movement of mobile users cannot remain at a constant velocity or absolute steady state but relatively small perturbations occur that can be regarded as Gaussian noise. Given that only a small portion of wireless users will exhibit high mobility [9], such a model is of some utility.

In the decentralized wireless networks designed to date, each mobile node has to observe the movement of other nearby nodes and try to estimate the state to implement the SCF relaying scheme. Here, this state is restricted to the position and velocity of the mobile subscriber wireless nodes. The observation cannot be ideal, and there is always some noise that enters the system. Generally, the KF algorithm is able to deal with two kinds of noise, namely measurement or sensor noise and transition or process noise [10]. Both types of noise are zero mean Gaussian in nature, and the dynamic and observation models are linear Gaussian. The filtering model presented above obeys the basic LQG regulator equations as mentioned before, so the filtering equation can be expressed as [11]:

$$\boldsymbol{x}_k = \mathbf{A}\boldsymbol{x}_{k-1} + \boldsymbol{q}_{k-1} \tag{4-4}$$

$$\boldsymbol{y}_k = \mathbf{H}\boldsymbol{x}_{k-1} + \boldsymbol{r}_k \tag{4-5}$$

where $\boldsymbol{x}_k$ is the hidden state vector and $\boldsymbol{y}_k$ is the observation vector at time k, respectively; $\boldsymbol{q}_{k-1} \sim N(0, Q)$ is the transition noise; $\boldsymbol{r}_k \sim N(0, R)$ is the sensor noise.

The movement of the mobile subscriber is described by two-dimensional Cartesian coordinates, so the hidden state vector has four dimensions $\boldsymbol{x}_k = (x_{k1}, x_{k2}, x_{k3}, x_{k4})$. The first two elements capture the position of the mobile node and the second two represent its corresponding velocity. The observation vector is $\boldsymbol{y}_k = (y_{k1}, y_{k2})$.

The matrices within the dynamic model are:

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{Q} = \begin{pmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{pmatrix}$$

where Δt is one second in the simulations and ***Q(i,j)*** is the transition covariance [10].

The matrices in the observation model are:

$$\mathbf{H} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$\mathbf{R} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

where ***R(i,j)*** is the observation covariance [10].

Here, the KF equations can be described as two steps [11]:

(i) prediction:

$$\boldsymbol{m}_k^- = \mathbf{A}_{k-1}\boldsymbol{m}_{k-1} \tag{4-6}$$

$$\boldsymbol{P}_k^- = \mathbf{A}_{k-1}\boldsymbol{P}_{k-1}\mathbf{A}_{k-1}^T + \boldsymbol{Q}_{k-1} \tag{4-7}$$

(ii) update:

$$\mathbf{S}_k = \mathbf{H}.\mathbf{P}_k^-.\mathbf{H}^T + \mathbf{R} \tag{4-8}$$

$$\mathbf{K}_k = \mathbf{P}_k^-.\mathbf{H}^T.\mathbf{S}_k^{-1} \tag{4-9}$$

$$\mathbf{m}_k = \mathbf{m}_k^- + \mathbf{K}_k.\{\boldsymbol{y}_k - \mathbf{H}.\mathbf{m}_k^-\} \tag{4-10}$$

$$\mathbf{P}_k = \mathbf{P}_k^- - \mathbf{K}_k.\mathbf{S}_k.\mathbf{K}_k^T \tag{4-11}$$

In which

$\boldsymbol{y}_k$ is the measurement at the time step *k*;

$\mathbf{P}_k$ is the covariance of a Kalman/Gaussian filter at the time step *k*;

$\mathbf{P}_k^-$ is the predicted covariance of a Kalman/Gaussian filter at the time step *k* just before the measurement $\boldsymbol{y}_k$;

$\boldsymbol{S}_k$is the innovation covariance of a Kalman/ Gaussian filter at step *k*;

$\mathbf{K}_k$ is the gain matrix of a Kalman/Gaussian filter;

$\mathbf{m}_k$ is the mean of a Kalman/Gaussian filter at the time step *k*;

$\mathbf{m}_k^-$ is the predicted mean of a Kalman/Gaussian filter at the time step *k* just before the measurement $\boldsymbol{y}_k$.

Before the filtering process starts, both the state vector **initial_state** (which is a column vector) and the state covariance vector **initial_V** have to be initialized thus (the initial values are chosen as 10 to avoid the start point of trajectory overlapping with original point on the coordinates):

$$\textbf{initial\_state} = \begin{pmatrix} 10 \\ 10 \\ 0 \\ 0 \end{pmatrix}$$

$$\textbf{initial\_V} = \begin{pmatrix} 10 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 \\ 0 & 0 & 10 & 0 \\ 0 & 0 & 0 & 10 \end{pmatrix}.$$

4.4 Simulations

4.4.1 Algorithm Simulation

To simulate the scenario studied, the true mobile user locations are generated by MATLAB [12] by adding random numbers to the values of X_1 and X_2 of previous step, which produces a stochastic linear dynamical system, which is a type of hidden state [10]. This is because the mobile node states cannot be directly measured by neighbouring mobile subscribers and KF algorithms are used for estimation. Fig. 4-2 illustrates the results of simulated KF algorithms using 50 individual states in each time step. These are the true states that simulate the real locations of the mobile subscriber during a continuous period of time, and that are represented by the black squares. The trajectory shown by the black line linking the black squares is the ‘real path’ of the motion of a certain mobile node. The blue stars indicate the observed location of the mobile device which simulates the measurements from another neighbouring mobile terminal. The red crosses show the KF outcomes, processed by the neighbouring mobile smart device with the estimated path represented by the red dotted line.

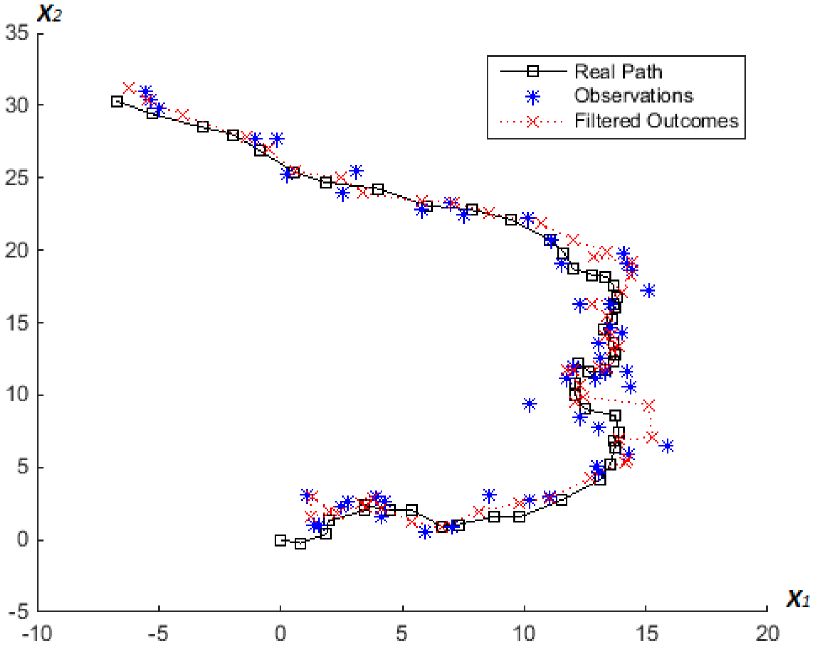


Fig. 4-2 Results of the prediction simulation for the filtering model.

It may be seen in Fig. 4-2 that for most of the time, the filtered trace represents the true path well. Only when the mobile user's movement is more dynamic (close to the maneuvering model), particularly the right-hand side of Fig. 4-2, does the algorithm have difficulty following the true path. Nevertheless, when the motion of the object exhibits behaviour that is close to the non-maneuvering scenario, the outcomes still reflect the real motion of the target very well as in the top and bottom parts of the trajectory, and the mismatched portion is relatively small.

4.4.2 Protocol Simulation

For testing the performance, resilience and tolerance of the DTN protocol designed, the sample dataset that was generated by the ONE simulator event generator was utilized to simulate a complex wireless network condition, which bases on the map that is used and the movement of moving objects collected. As has been described in Section 3.5.2, the map data is the downtown area of Helsinki city which includes road and pedestrian walk paths. The connectivity traces for the real time location data of various moving objects carrying with the mobile device, such as pedestrians, cars and trams, are generated by the ONE simulator. Parameters for the simulation configurations are specified in Table 4-1. These are chosen to be of the same order as the parameters in [13] with the buffer size large enough that it does not impact performance.

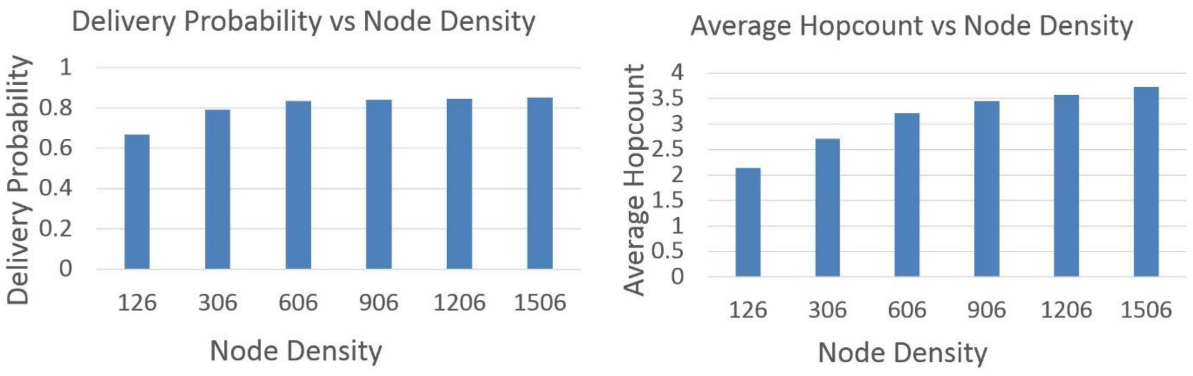
TABLE 4-1 PARAMETERS OF SIMULATION CONFIGURATIONS

Parameters	Value of parameters
Dimension (meter)	8300 X 7300
Buffer Size (MB)	50
Message Time To Live (TTL) (minute)	100
Message Interval (second)	3, 5, 10, 20, 30, 60
Message Size (kB)	500
Total Number of Nodes	126, 306, 606, 906, 1206, 1506
Simulation Time (second)	86400
Transmit Range (meter)	20 – 1500
Transmit Speed (kBps)	250 – 10000

The message interval simulated the information rate of the sender. The parameters for this category tested the circumstances from a low packet generation rate of 1 packet per minute (67 kbps) to a high packet generation rate of 20 packets per minute (1.33 Mbps). The number of nodes varied the density of the wireless system from a low-density (40 nodes) mobile network to an extremely high-density (1506 nodes) system.

In this part of work, there are four key factors of the wireless system that are addressed to evaluate the overall performance of proposed mobile routing strategy, which are: Delivery Probability, Overhead Ratio, Average Latency and Average number of hops. The variety of simulation parameters against different performance metrics are given as follows:

4.4.2.1 Node Density

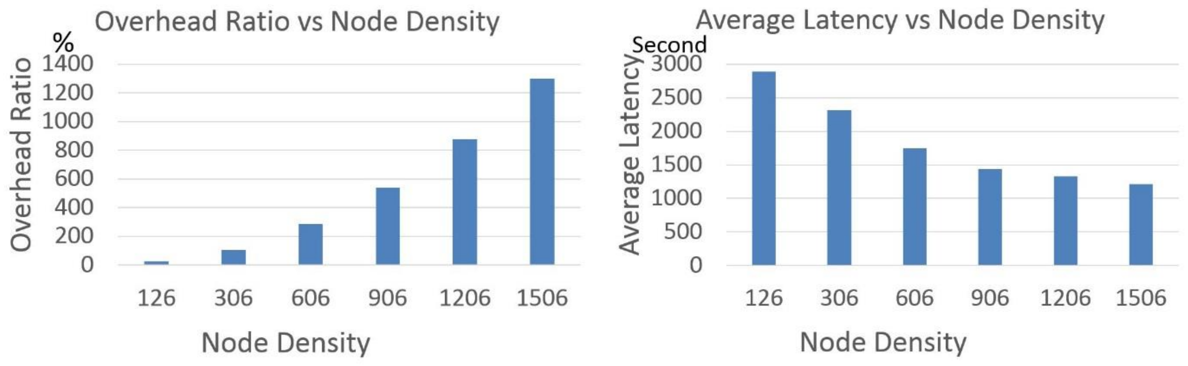


(a) (b)

Fig. 4-3 (a) Delivery probability; (b) average hop count for different network densities.

Fig. 4-3 shows the performance of the proposed protocol at the maximum bit rate considered. It provides good resilience for different network densities and maintains a delivery probability in excess of 0.7 for all circumstances. Moreover, as the algorithm is able to predict the movement of portable nodes, the protocol delivers an average hop count of between 2.1 and 3.7, leading to the involvement of fewer intermediate nodes in the relaying path saving retransmission energy and improving efficiently.

Fig. 4-4 shows that the overhead ratio rises sharply with the number of nodes since there are more possible packet relay candidates. However, there is a corresponding decrease in the average latency as there are more nodes that can complete delivery. The balance of these two factors makes the protocol able to maintain useful performance when the network setup changes.

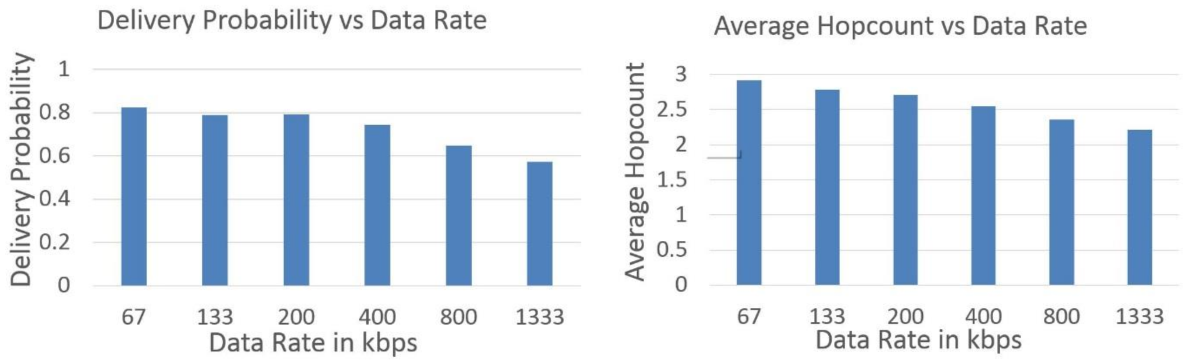


(a) (b)

Fig. 4-4 (a) overhead ratio; (b) average latency for different network densities.

4.4.2.2 Data Rate

To test the capability of the protocol to deal with various traffic volumes, the packet generation rate in a network comprising 126 nodes was varied. Fig. 4-5 illustrates the variation in delivery probability and hop count as the data rate increases. The former drops with increasing traffic volumes but the KaFiR protocol still maintains a probability of approximately 0.6 whilst the hop count falls from almost three to a little over two with increasing bit rate.

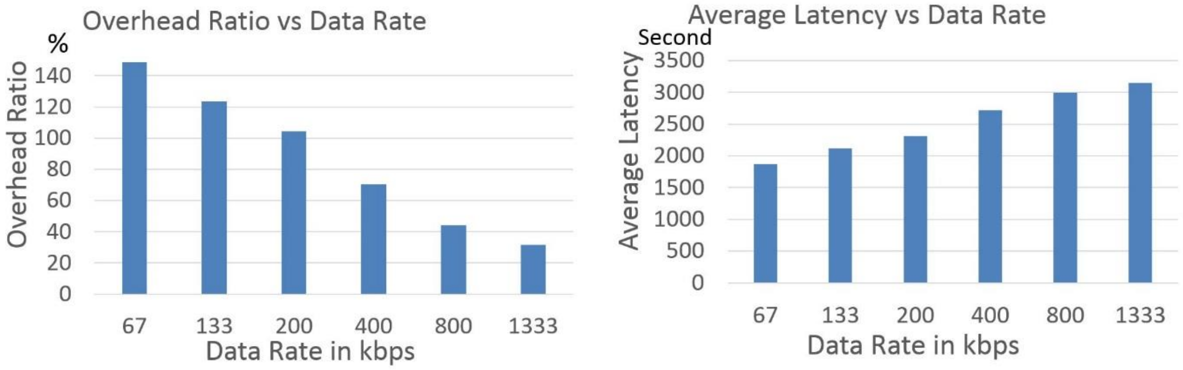


(a) (b)

Fig. 4-5 (a) Delivery probability; (b) average hop count as a function of data rate for low node density.

Fig. 4-6 shows that the overhead ratio decreases from 148% to 31% as the bit rate increases but this is accompanied by an increase in average Latency from 1875 seconds to 3153 seconds.

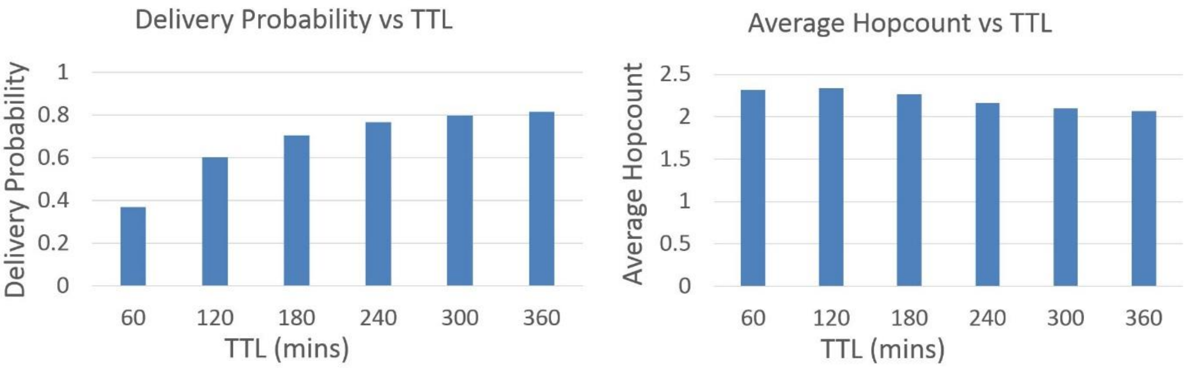
The KaFiR relaying scheme exhibits acceptable overall performance which benefits from the portable device movement predication ability allow more packets to arrive successfully at the receiver or be relayed to the correct intermediate nodes. This feature maintains the delivery probability at a high value whilst and keeping the average hop count at a low level.



(a) (b)

Fig. 4-6 (a) Overhead ratio; (b) average latency as a function of data rate for low node density.

4.4.2.3 Time To Live

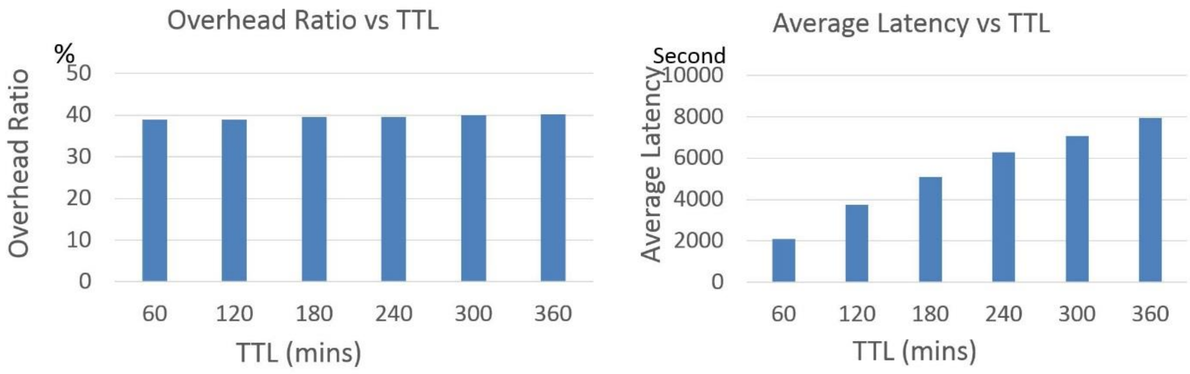


(a) (b)

Fig. 4-7 (a) Delivery probability; (b) average hop count for different TTL in mins.

Fig. 4-7 (a) shows that the delivery probability increases constantly when TTL grows from 60 to 360 mins and reaches 0.8 when TTL has the maximum value at 360 mins. The outcome implies that a large TLL gives more opportunities for the system to deliver to its destination, a longer lifespan allows the message to suffer a longer waiting time.

Fig. 4-7 (b) presents that the number of average hop counts benefits from the increasing of TLL. When TTL is 360 mins, the messages are delivered using only approximately two hops.

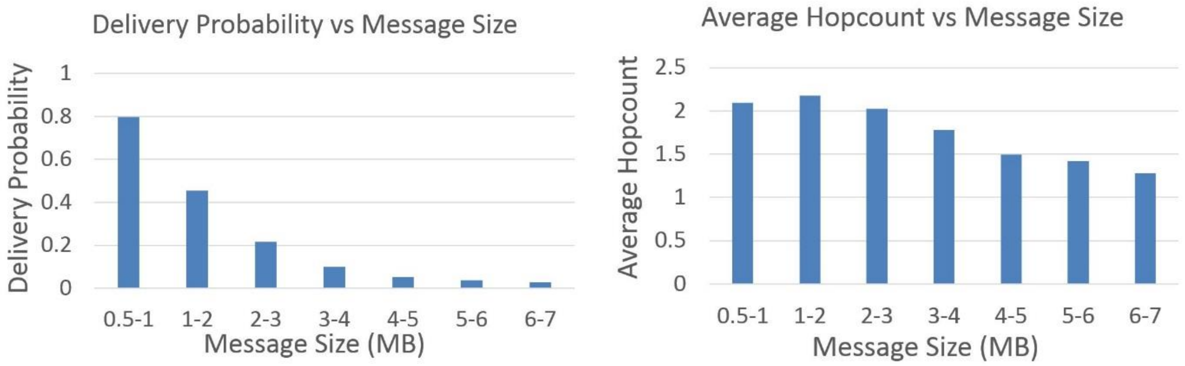


(a) (b)

Fig. 4-8 (a) overhead ratio; (b) average latency for different TTL in mins.

In Fig. 4-8, the overhead ratio has a constant performance that does is affected by the lifetime of messages. However, the average latency increases almost four times from 2000 seconds to most 8000 seconds, which is mainly because the messages are allowed to remain in the system for a longer period.

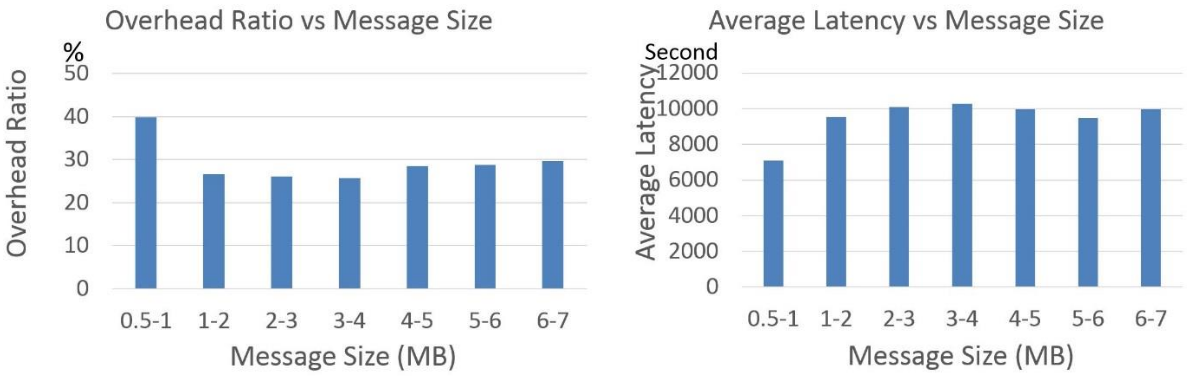
4.4.2.4 Message Size



(a) (b)

Fig. 4-9 (a) Delivery probability; (b) average hop count for different message size.

Fig. 4-9 indicates that the delivery probability drops dramatically by the increasing of the message size. It becomes less than 0.1 when message size exceeds 3 to 4 MB, which is even not feasible for most of DTN applications and services. However, DTN applications do not require such large message size normally. This problem can be solved by splitting large messages into many small segments and encapsulating these into multiple appropriate data packets. The average hop count slightly decreases when message size gets larger.

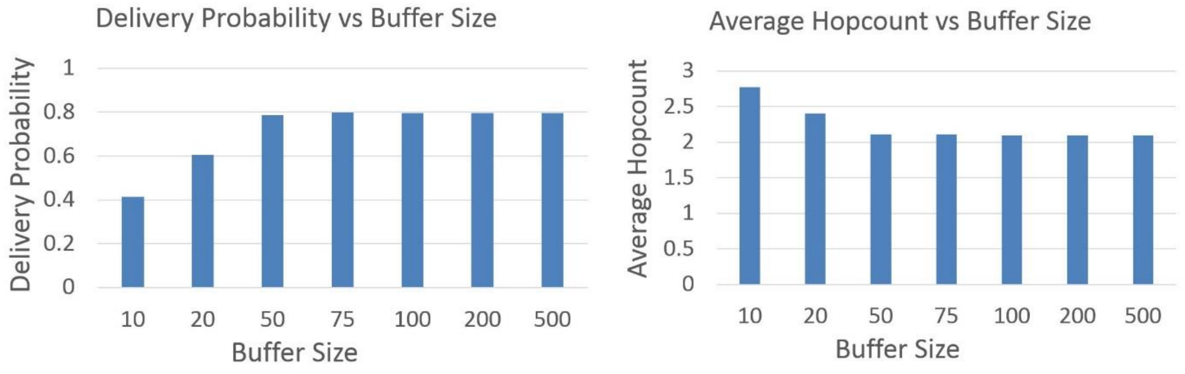


(a) (b)

Fig. 4-10 (a) overhead ratio; (b) average latency for different message size.

Fig. 4-10 presents that the overhead ratio and average latency do not have a stable moving trend by the change of message size. The overhead ratio reaches a minimum of around 25% when the message size is between 3 and 4 MB, and the highest figure is almost 40% as the message size is 0.5 to 1 MB. The average latency does not change significantly, having only a small variation near 10000 seconds apart from 7000 seconds for small messages.

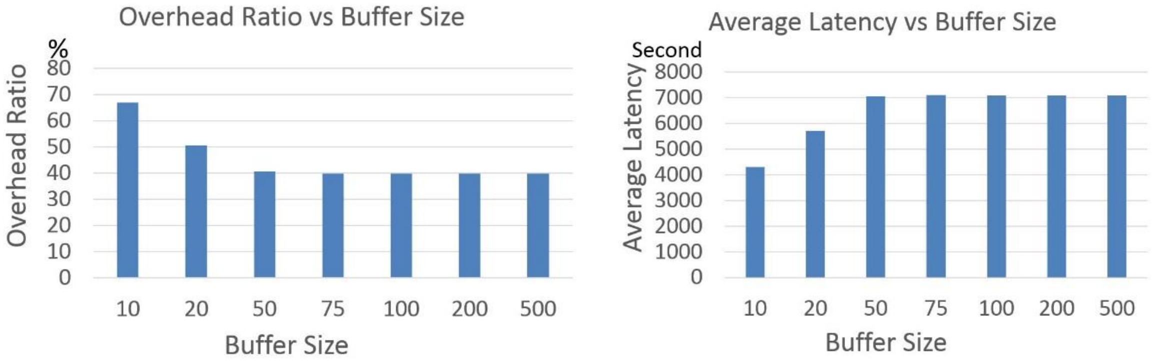
4.4.2.5 Buffer Size



(a) (b)

Fig. 4-11 (a) Delivery probability; (b) average hop count for different buffer size.

Fig. 4-11 implies that the delivery probability and average hop count will not be affected after the buffer size on the portable terminals exceeds 50 MB. The delivery probability increases from 0.4 when buffer size is 10MB and stays at 0.8, and average hop count drops from 2.8 as buffer size is 10MB and remains at around 2.1.



(a) (b)

Fig. 4-12 (a) overhead ratio; (b) average latency for different buffer size.

Fig. 4-12 shows that the overhead ratio and average latency have the same performance as the delivery probability and average hop count that were shown in Fig. 4-11. The overhead ratio declines down from 67% to 40% and remains at this ratio after buffer size exceeds 50 MB.

As it can be seen from Fig. 4-11 and Fig. 4-12, when the smart node buffer size reaches 50MB, the key performance evaluation factors of DTN system will not change any more by increasing of the buffer capacity. This result just falls into the characteristics of the majority of smart devices in DTN system.

4.5 Simulation Comparisons

As mentioned in Section 3.5.2, to evaluate the performance of algorithm designed, the routing protocol will be tested in two kinds of network conditions: a simple wireless network and a complex wireless network. The dataset of the simple wireless network is the real trace of mobile users downloaded from CRAWDAD datasets [14]. To convert GPS traces into ONE connectivity traces, the circular communication range of each mobile node has been assumed be 200 meters. The dataset of the complex wireless network is the same ONE simulator dataset used for the protocol simulation in Section 4.4.2. Parameters for the simulation configurations are specified in Table 4-2.

TABLE 4-2 PARAMETERS OF SIMULATION CONFIGURATIONS

	Label on the graphs	**Value of parameters**
Buffer Size (MB)	B	10, 20
Message Time To Live (TTL) (minute)	T	30
Message Interval (second)	I	1, 5
Message Size (kB)	M	10, 20, 200
Total Number of Nodes	H	156, 231, 306, 486, 606 (only for simple network)
Simulation Time (second)		86400
Protocol		The KaFiR, Epidemic, Direct Delivery, SprayandWait (Binary version), SprayandFocus

4.5.1 Simple Network

Fig. 4-13 shows that in a simple mobile network, when it is sparse, the KaFiR relaying scheme and other routing plans give approximately the same delivery probability around 0.03 in various scenarios. For the SprayandFocus scheme, when the message interval is high, delivery probability is higher than 0.08, however, when the message rate is high, delivery probability is at most 0.05.

In Fig. 4-14 and Fig. 4-15, it is shown that the delivery probabilities of different wireless routing strategies do not change significantly from Low Density to High Density networks, which indicates for the simple network, when the network density reaches a certain level, the growth of number of mobile nodes cannot help to increase the delivery probability, as the opportunities for node encounters relatively low and this limits the chance for messages to be received by the destination nodes.

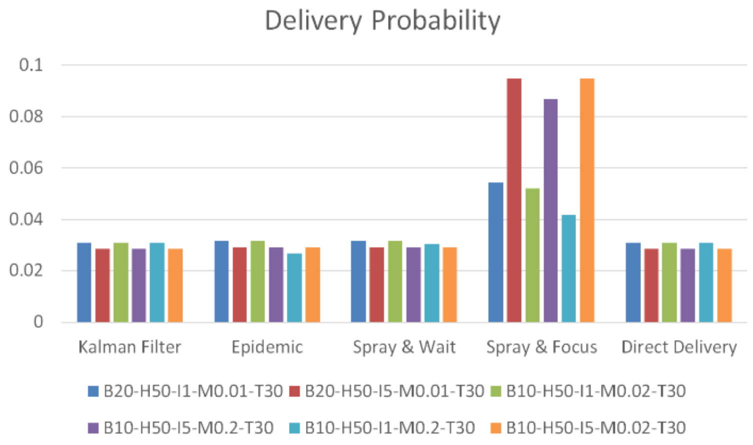


Fig. 4-13 Delivery Probability for Sparse (156 nodes) Simple Network.

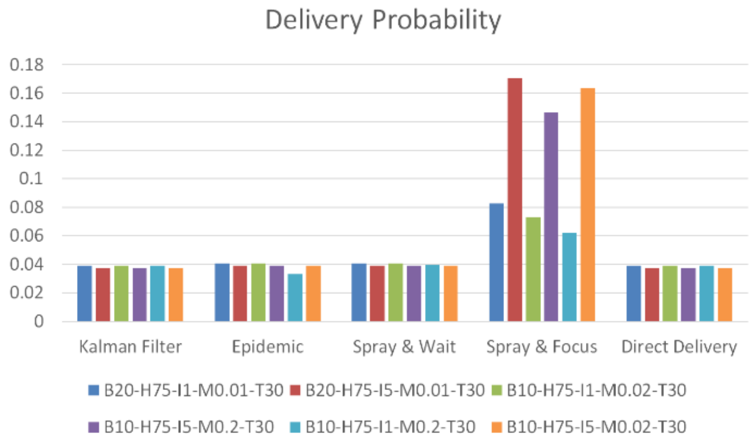


Fig. 4-14 Delivery Probability for Low Density (231 nodes) Simple Network.

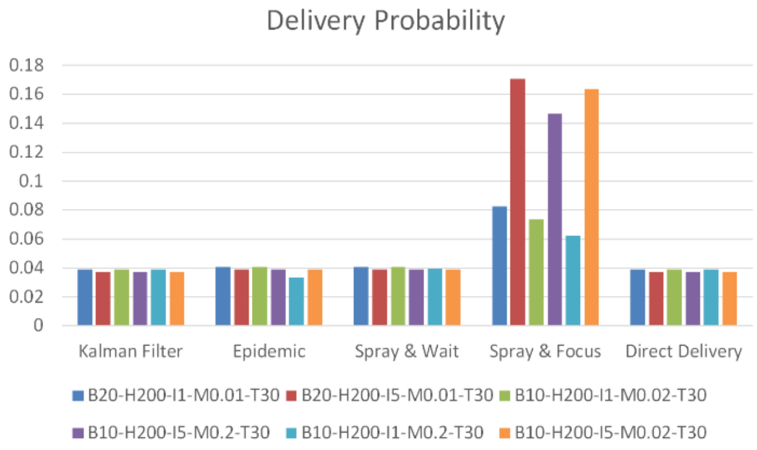


Fig. 4-15 Delivery Probability for High Density (606 nodes) Simple Network.

The KaFiR routing protocol uses statistical methods to determine the next hop selection. For the simple system, it is easy for a source node to learn whether it will encounter the destination by statistical inference. The protocol can keep its Overhead Ratio close to zero, which be close to the Direct Delivery relaying scheme.

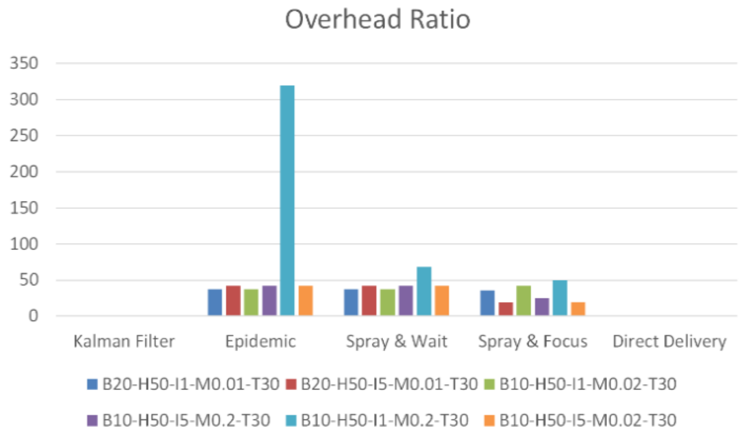


Fig. 4-16 Overhead Ratio for Sparse (156 nodes) Simple Network.

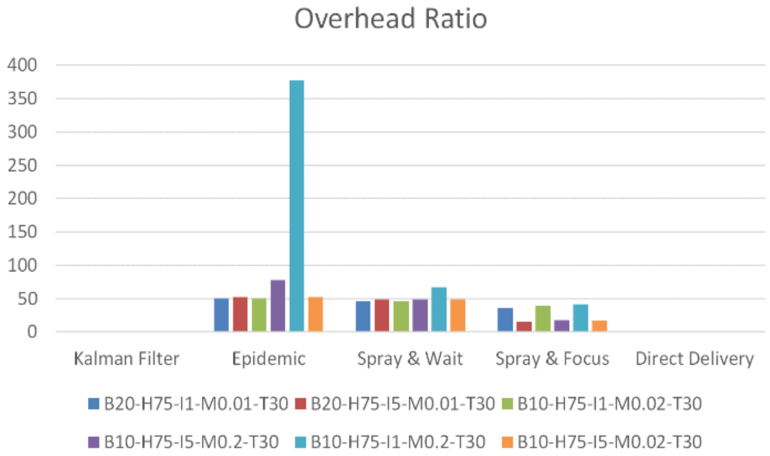


Fig. 4-17 Overhead Ratio for Low Density (231 nodes) Simple Network.

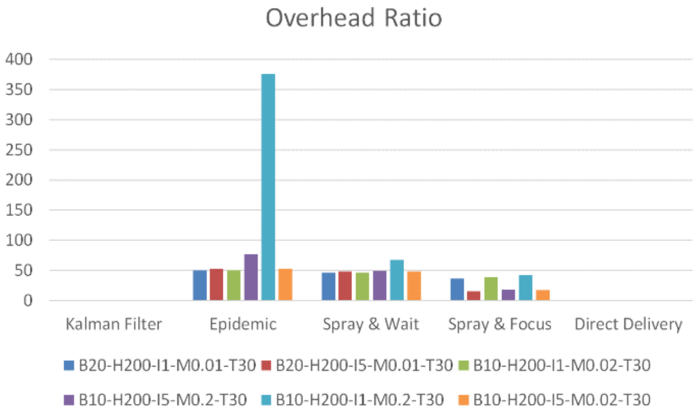


Fig. 4-18 Overhead Ratio for High Density (606 nodes) Simple Network.

In Fig. 4-16, Fig. 4-17 and Fig. 4-18, the overall Overhead Ratio of the sparse network is a little lower than other dense networks. After the population of nodes reaches 231, then the Overhead Ratio becomes steady.

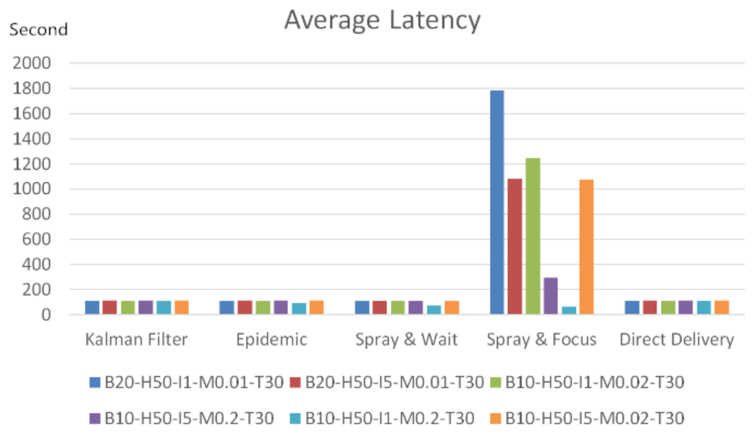


Fig. 4-19 Average Latency for Sparse (156 nodes) Simple Network.

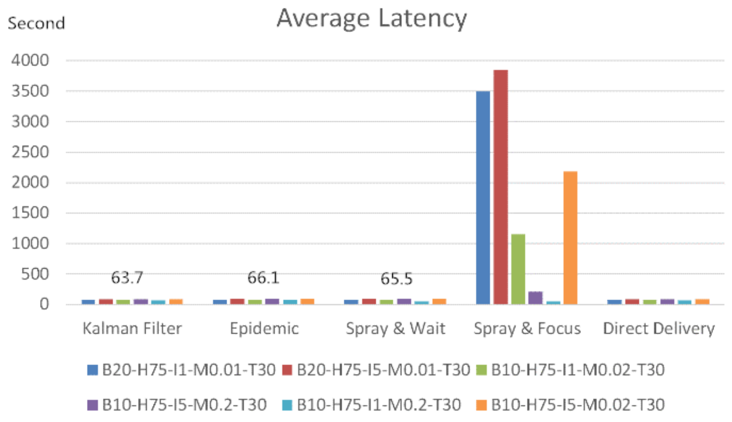


Fig. 4-20 Average Latency for Low Density (231 nodes) Simple Network.

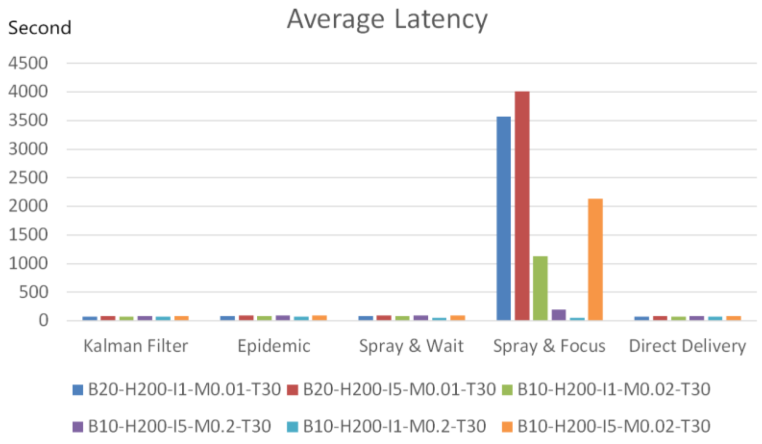


Fig. 4-21 Average Latency for High Density (606 nodes) Simple Network.

In Fig. 4-19, Fig. 4-20 and Fig. 4-21, all protocols, except the SprayandFocus scheme, deliver low degrees of average latency avoiding long packet delivery delays.

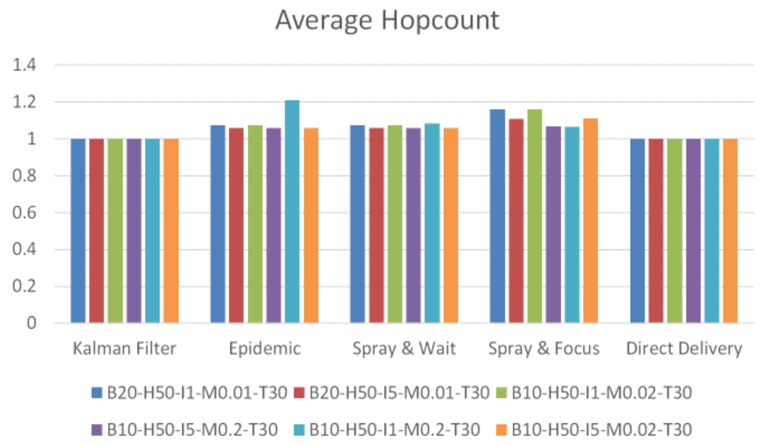


Fig. 4-22 Average Hopcount for Sparse (156 nodes) Simple Network.

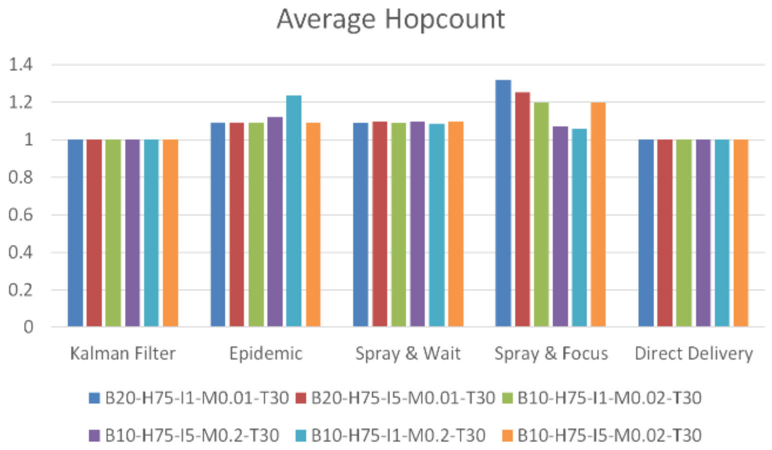


Fig. 4-23 Average Hopcount for Low Density (231 nodes) Simple Network.

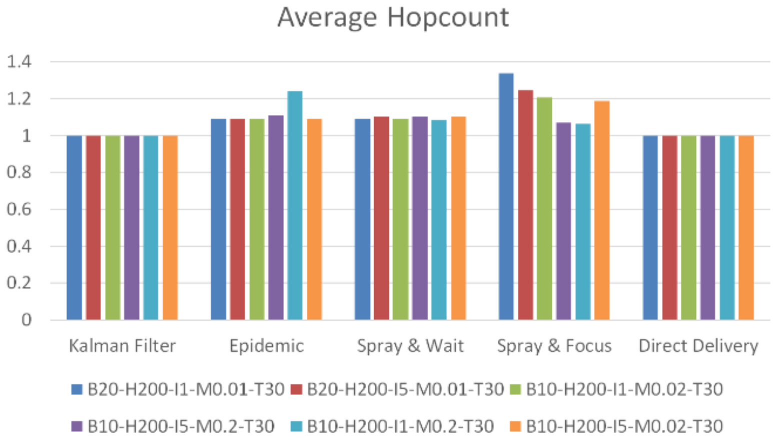


Fig. 4-24 Average Hopcount for High Density (606 nodes) Simple Network.

As the KaFiR protocol tends to use the Direct Delivery method, it keeps the average hop count at one hop in common with the Direct Delivery protocol. Fig. 4-22, Fig. 4-23 and Fig. 4-24 indicate that there is no significant difference between various network densities for simple networks but for some scenarios, SprayandFocus presents a slightly higher average hop count than other protocols.

4.5.2 Complex Network

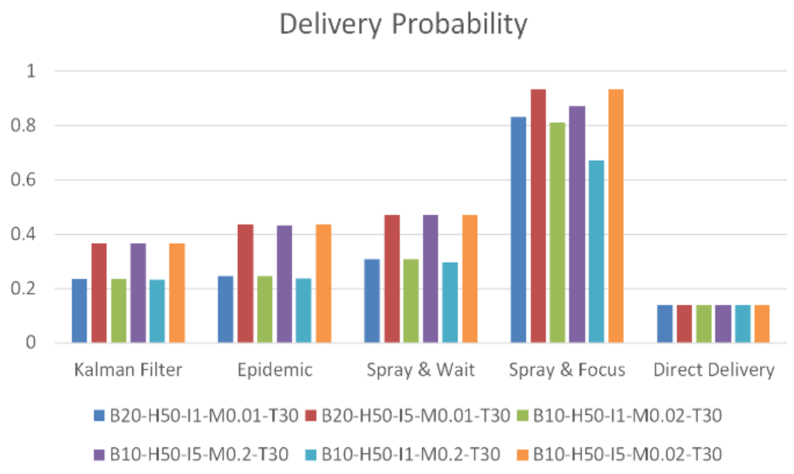


Fig. 4-25 Delivery Probability for Sparse (156 nodes) Complex Network.

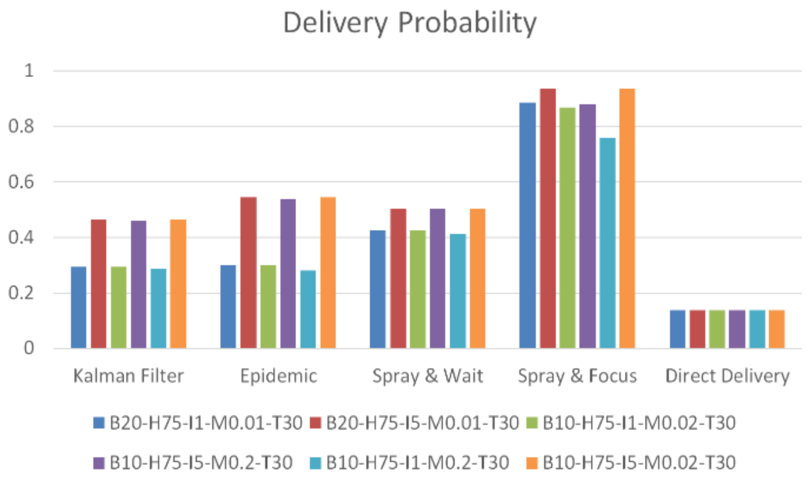


Fig. 4-26 Delivery Probability for Low Density (231 nodes) Complex Network.

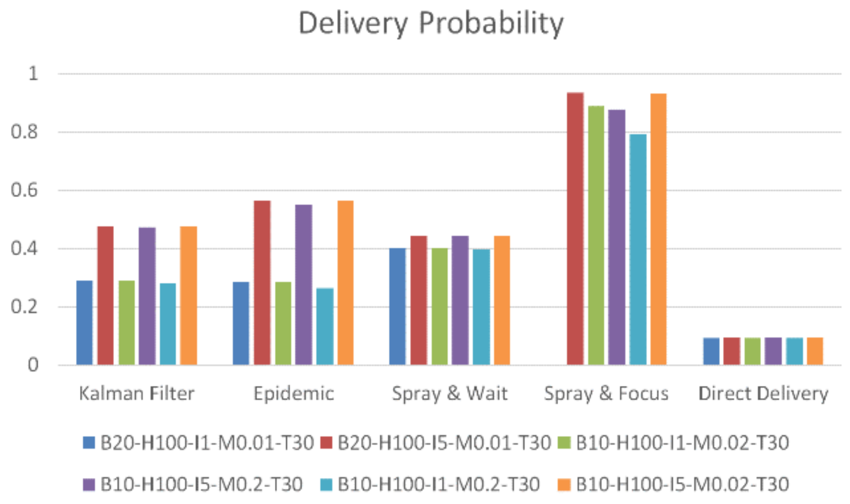


Fig. 4-27 Delivery Probability for MidLow Density (306 nodes) Complex Network.

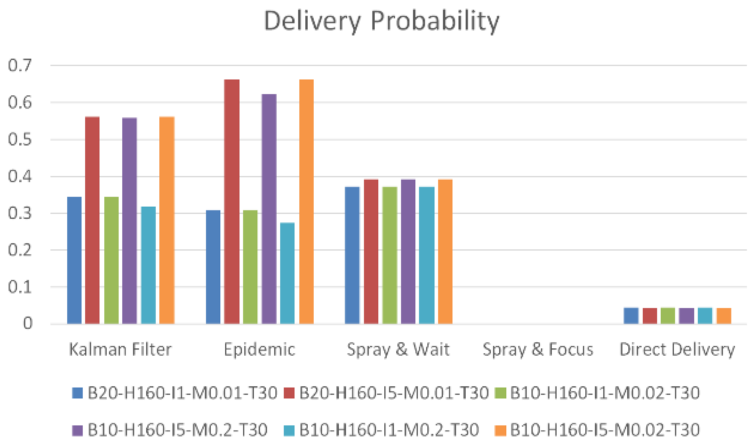


Fig. 4-28 Delivery Probability for Density (486 nodes) Complex Network.

From Fig. 4-25 to Fig. 4-28, the delivery probabilities of the KaFiR and Epidemic routing plans show a stable increase and tolerance when the number of wireless nodes increases, especially, in a dense network, they are the best two relaying schemes as long as the message rate is low. In contrast, the delivery probabilities of SprayandWait and Direct Delivery drop slightly when the network density grows. SprayandFocus provides a significantly higher delivery probability than other protocols and also benefits from the increasing number of portable nodes, however SprayandFocus is unable to work well in the dense network.

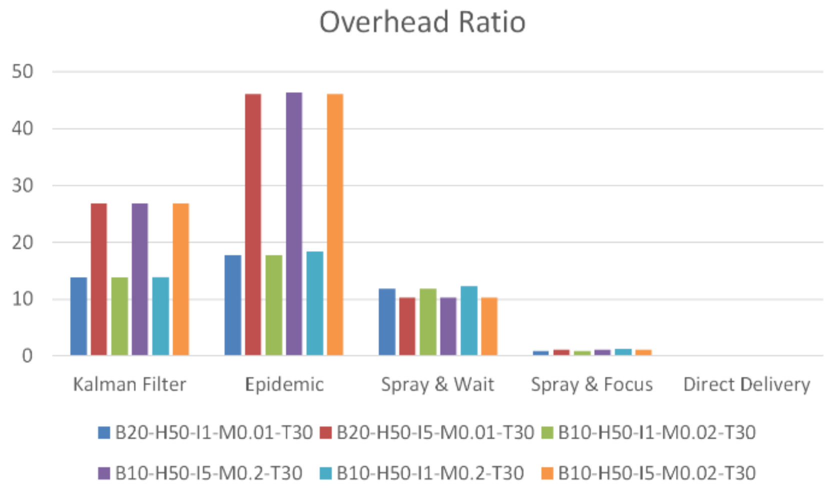


Fig. 4-29 Overhead Ratio for Sparse (156 nodes) Complex Network.

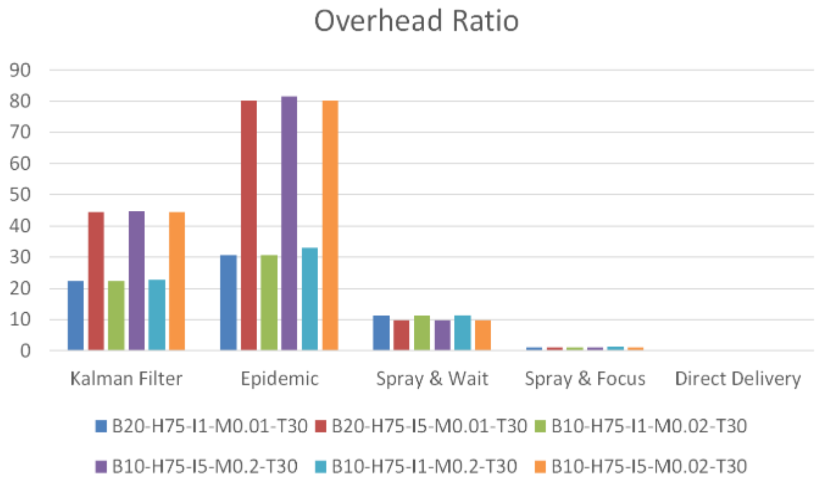


Fig. 4-30 Overhead Ratio for Low Density (231 nodes) Complex Network.

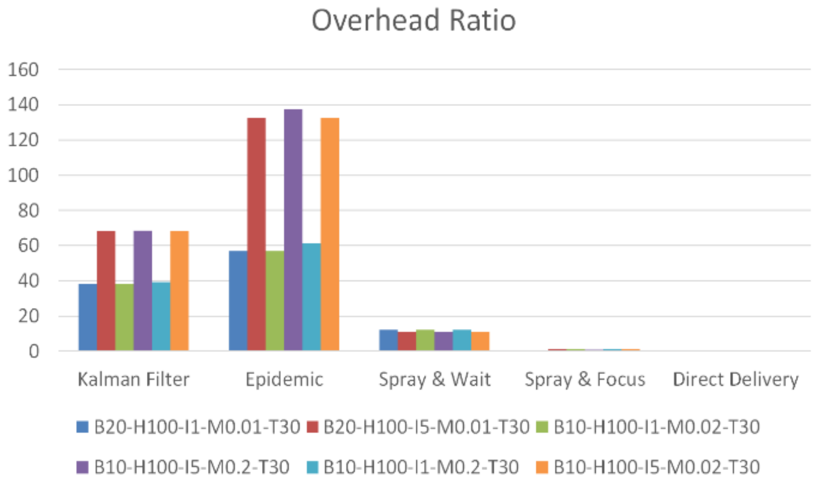


Fig. 4-31 Overhead Ratio for MidLow Density (306 nodes) Complex Network.

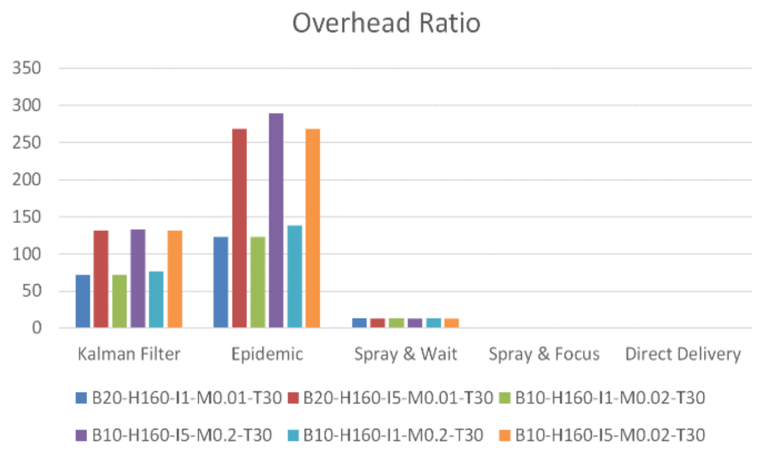


Fig. 4-32 Overhead Ratio for Density (486 nodes) Complex Network.

From Fig. 4-29 to Fig. 4-32, it may be seen that in a complex network, the KaFiR protocol does not mainly rely on a Direct Delivery strategy. Instead, it predicts the movement of neighbouring nodes to find the best relaying node, so the overhead ratio does not remain at zero since prediction of the probability of a source node encounter with a destination node becomes increasing difficult with the number of nodes. As the outcomes show from Fig. 4-33 to Fig. 4-36, the average hop count for the KaFiR scheme also does not remain at one as in the simple network but rather grows with the network scale.

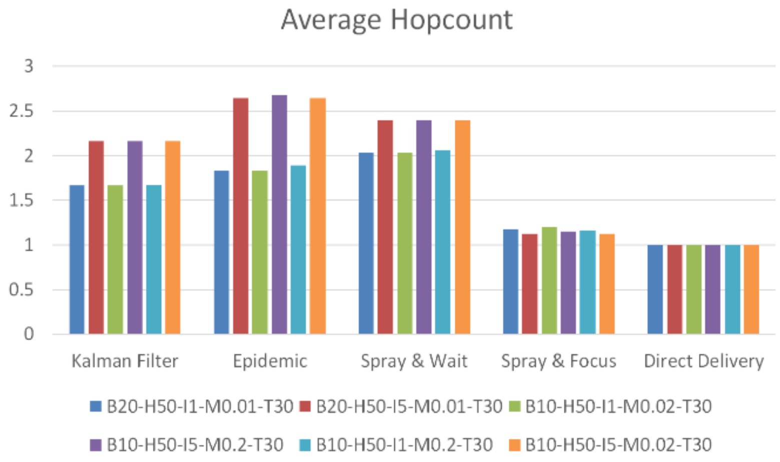


Fig. 4-33 Average Hopcount for Sparse (156 nodes) Complex Network.

In contrast, SprayandFocus keeps the overhead ratio at a low level, and it reduces with the growth in the number of mobile nodes, which is reflected in the average hop count and shows that the strategy needs very close to one hop for the entire message route. The overhead ratio and average hop count for SprayandWait stay in narrow ranges of 9% to 14% for the overhead ratio, and 2 to 3 for the average hop count.

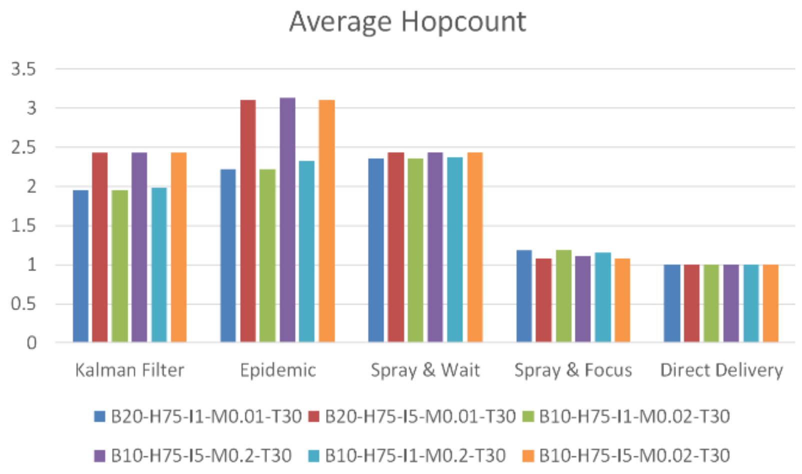


Fig. 4-34 Average Hopcount for Low Density (231 nodes) Complex Network.

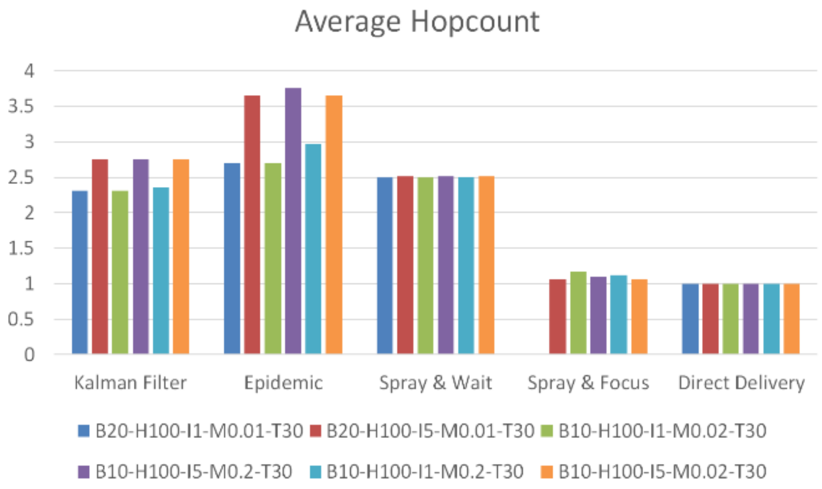


Fig. 4-35 Average Hopcount for MidLow Density (306 nodes) Complex Network.

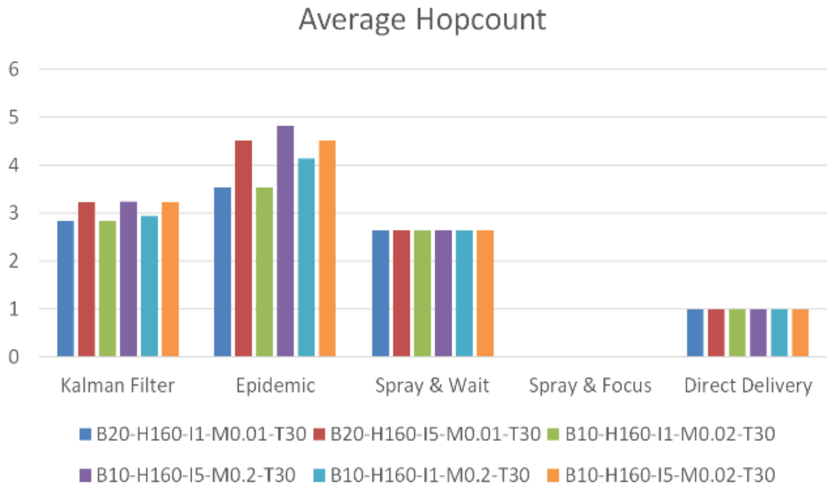


Fig. 4-36 Average Hopcount for Density (486 nodes) Complex Network.

From Fig. 4-37 to Fig. 4-40, the graphs indicate that the average latency of SprayandFocus is significantly higher than the other protocols in some scenarios, and it goes down when the number of nodes goes up. The average latency for rest of the protocols stays at about the same level for all the tests.

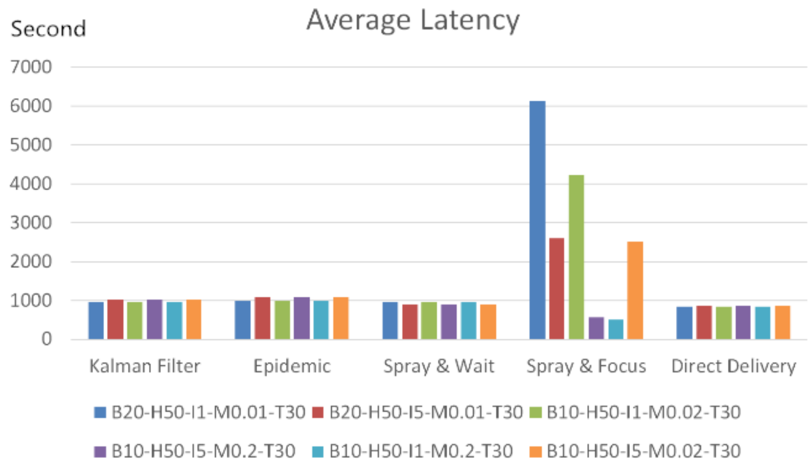


Fig. 4-37 Average Latency for Sparse (156 nodes) Complex Network.

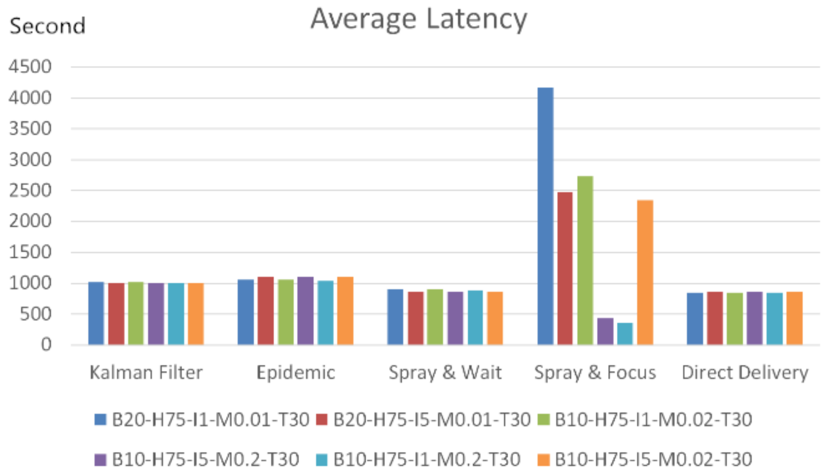


Fig. 4-38 Average Latency for Low Density (231 nodes) Complex Network.

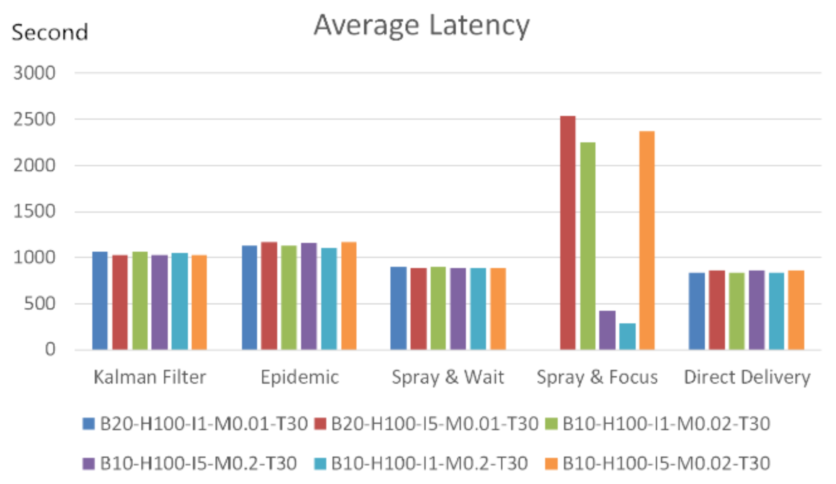


Fig. 4-39 Average Latency for MidLow Density (306 nodes) Complex Network.

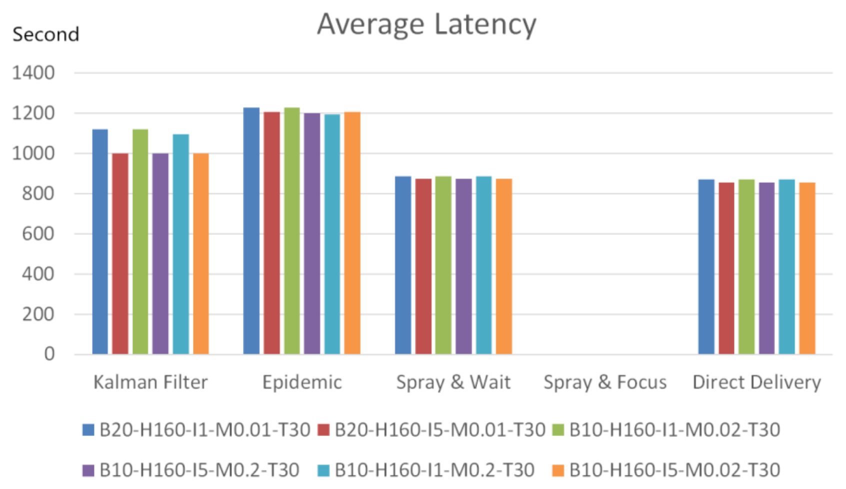


Fig. 4-40 Average Latency for Density (486 nodes) Complex Network.

4.5.3 Comparison among different routing protocols

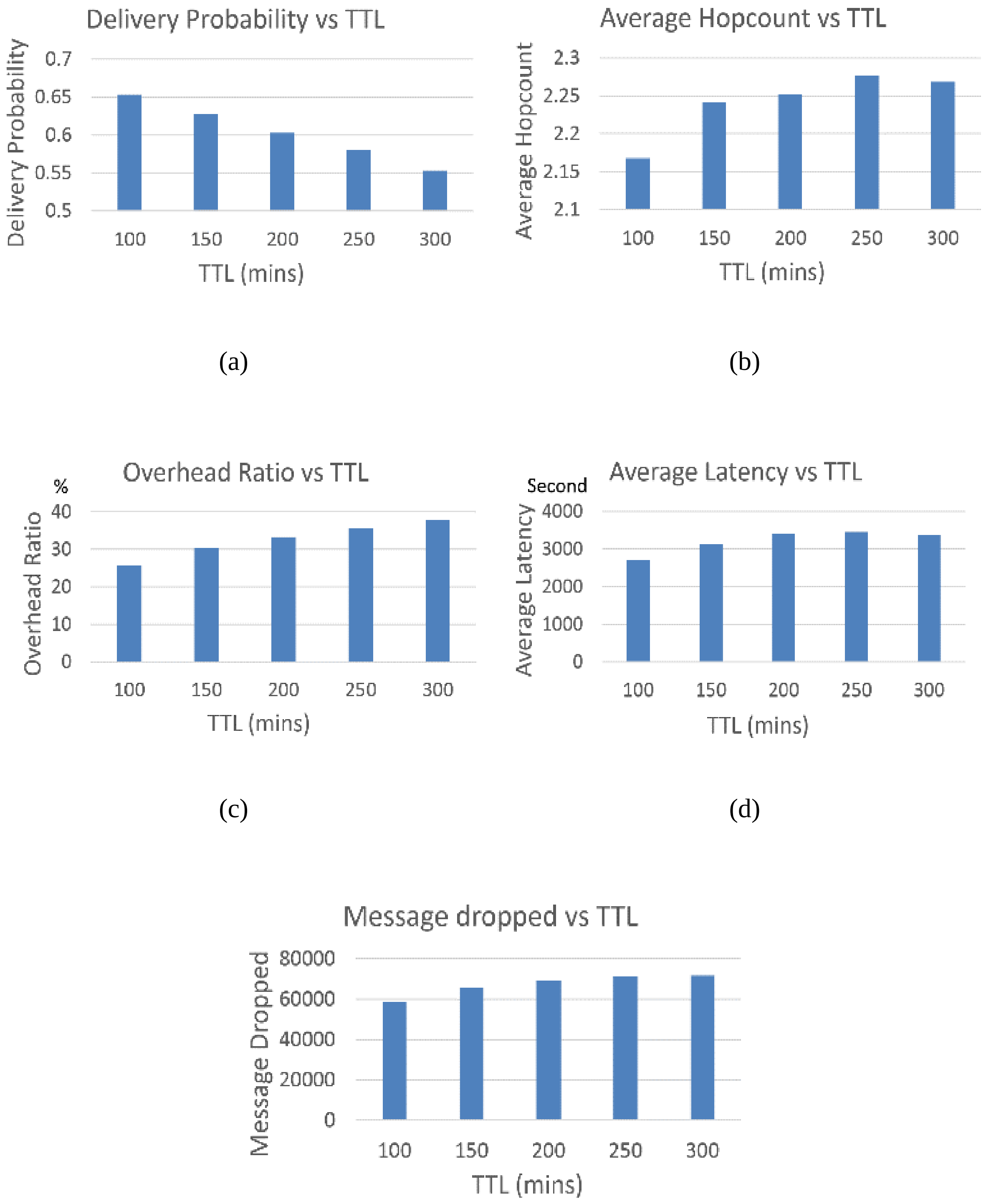
In both simple mobile networks and complex wireless networks, Epidemic routing protocol has a poor overall performance comparing with other DTN routing protocols. Epidemic does not apply any prediction measurement into the message routing control, and simply bases on a flooding mechanism that causes a higher over radio than other relaying algorithms in almost of seminars, as large volume of redundant data messages are circulating in the network. The flooding strategy only lets Epidemic has a similar delivery probability as other protocols. However, average hop count and average latency are higher in most of seminars, due to the data packets are relayed randomly and relaying paths are not optimised.

SprayAndWait is one of multiple-copy schemes with semi flooding mechanism, which applies a controlled flooding strategy to minimise the number of message duplicates. As it has been mentioned in Section 2.3, in the Spray phase, the message carrying nodes transfer the message to the first encountered node then use direct delivery strategy, which means the relaying scheme has no mechanism applied to choose the better or best intermediate relaying hop among the candidate nodes. As the less management of routing optimisation, the protocol does not present an outstanding overall performance.

SprayAndFocus relaying strategy is the upgraded strategy of SprayAndWait, in which the latter phase in the delivery strategy is replaced by a sophisticatedly designed utility-based scheme that helps the system optimise the message routing path and improves the performance from SprayAndWait protocol.

4.5.4 Comparison with a very recent protocol

DTN is a significant emerging paradigm in the wireless communication domain, and there has been much research concerning routing algorithms and relaying strategies to improve the system performance. Game Theoretic Approach for Context Based Routing (GT-ACR) is one of the latest DTN routing protocols. In [15], GT-ACR has been tested in delivery probability, average hop count, overhead ratio, average latency and number of messages dropped against various time to live, number of nodes and message interval. Here, the KaFiR relaying scheme is tested in the same series of metrics to compare its overall performance to this latest routing protocol with the results in Fig. 4-41 to Fig, 4-43 respectively, and the comparisons for each factor are listed in Table 4-3.

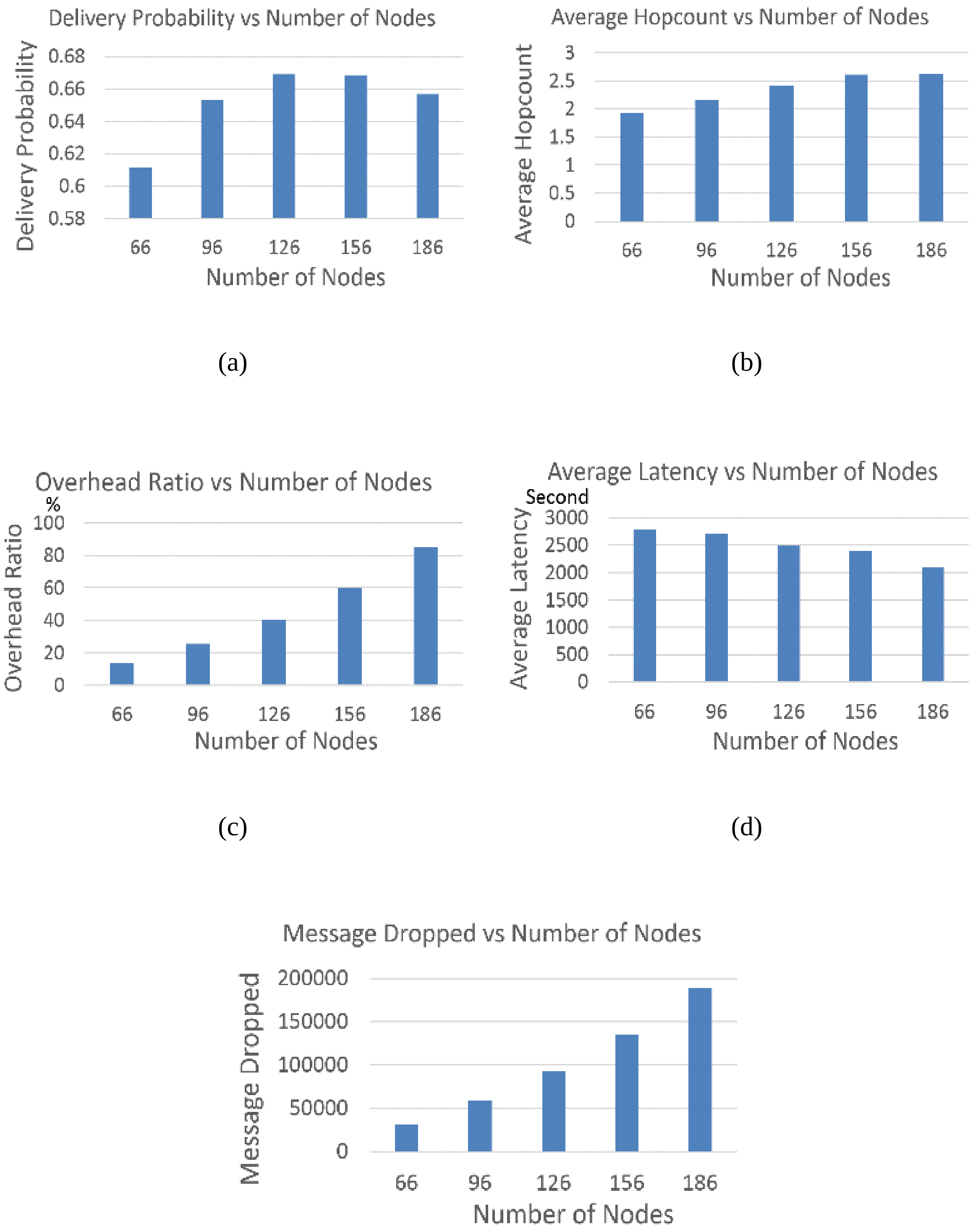


(a) (b)

(c) (d)

(e)

Fig. 4-41 (a) Delivery probability; (b) average hop count; (c) overhead ratio; (d) average latency; (e) number of messages dropped for different TTL.

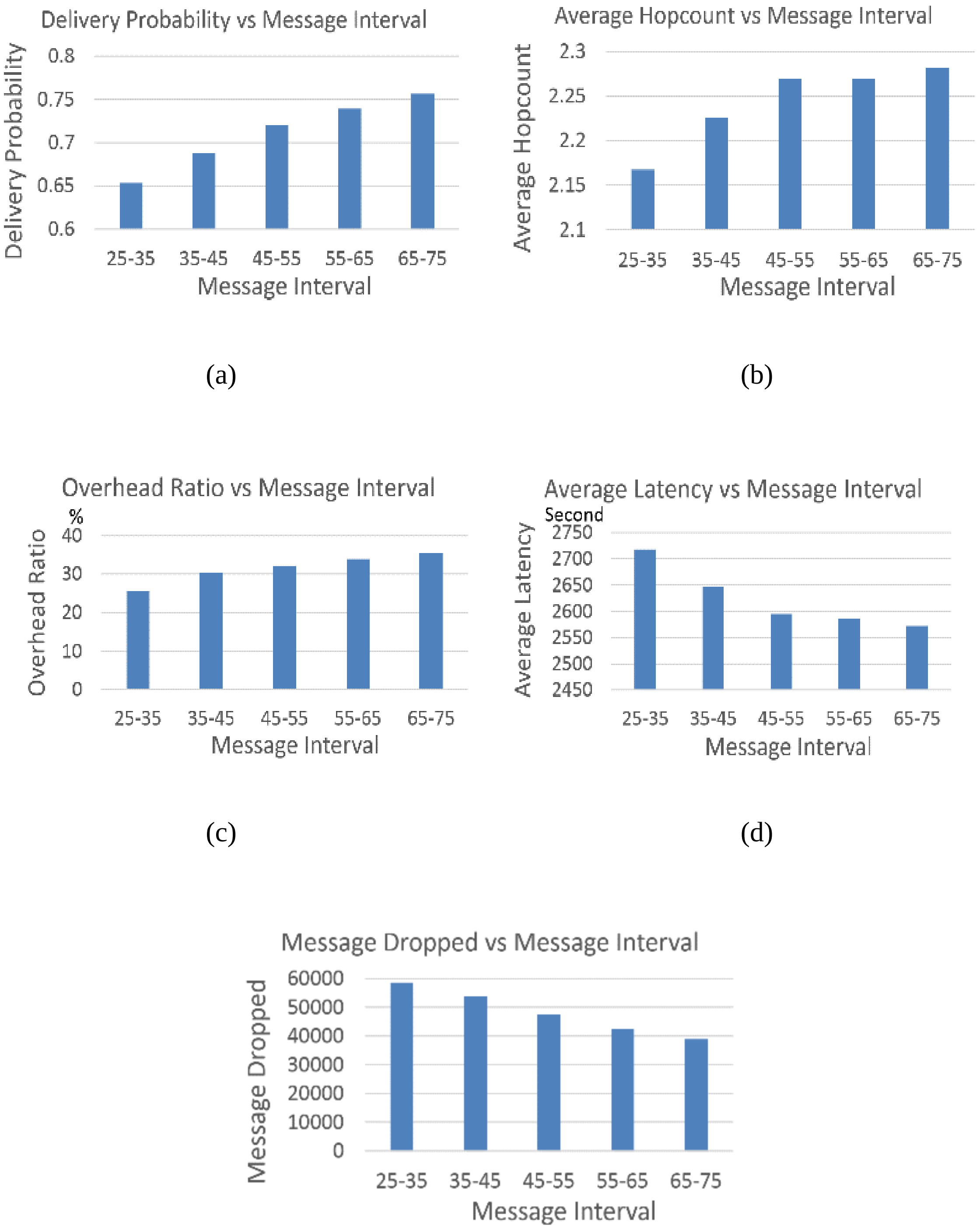


(a) (b)

(c) (d)

(e)

Fig. 4-42 (a) Delivery probability; (b) average hop count; (c) overhead ratio; (d) average latency; (e) number of messages dropped for different number of nodes.



(a) (b)

(c) (d)

(e)

Fig. 4-43 (a) Delivery probability; (b) average hop count; (c) overhead ratio; (d) average latency; (e) number of messages dropped for different message generation intervals.

TABLE 4-3 COMPARISON BETWEEN KAFIR AND GT-ACR ROUTING PROTOCOLS

	Performance factor	Mean of each factor	
		KaFiR	GT-ACR [15] (from Borah, 2017)
TTL	Messages Dropped	67381.4	91041.4
	Delivery Probability	0.60	0.54
	Overhead Ratio	32.54%	52.07%
	Average Latency	3216.2 s	2513.2 s
	Average Hopcount	2.24	2.42
Number of Nodes	Messages Dropped	101447	152661
	Delivery Probability	0.65	0.53
	Overhead Ratio	44.93%	66.52%
	Average Latency	2501.6 s	2200.4 s
	Average Hopcount	2.35	2.54
Message Interval	Messages Dropped	48233.6	66969
	Delivery Probability	0.71	0.69
	Overhead Ratio	31.52%	42.52%
	Average Latency	2623.5 s	2361.3 s
	Average Hopcount	2.24	2.42

In comparisons above between the KaFiR routing scheme and GT-ACR routing protocol with various values of TTL, number of nodes and message intervals, Table 4-4 gives the various values for the test parameters. The KaFiR routing protocol delivers an outstanding performance for almost all of the factors, particular in the number of messages dropped and overhead ratio, the KaFiR performs 35% to 50% and 35% to 60% better than GT-ACR respectively. For data packet delivery probability, the KaFiR presents 3% to 22% better performance. Regarding average hop count, the proposed algorithm offers an average of 8% better. Only on average latency, is the KaFiR 11% to 28% behind GT-ACR.

TABLE 4-4 PARAMETERS FOR COMPARISON

Parameter	Value	Unit
Time To Live (TTL)	100, 150, 200, 250, 300	Minute
Number of nodes	66, 96, 126, 156, 186	Node
Message intervals	25-35, 35-45, 45-55, 55-65, 65- 75	Second

The comparison results show that the KaFiR has a significant performance among the latest DTN routing protocols, it only makes a small sacrifice in the message delay to get significant improvements on others wireless system performance metrics.

4.6 Summary

In simple mobile networks, the performance for all relaying schemes is very stable as there is little difference for various network densities. In comparison to other routing plans, the KaFiR strategy delivers similar performance apart from SprayandFocus, with fewer hops, which can save transmission energy for the entire relaying process and help to improve network security. SprayandFocus offers a higher delivery probability but this comes at the cost of an extremely high average latency. Such a long delay might not be applicable for some applications, even in a DTN system.

For complex wireless networks, the routing strategies test results show a significantly different performance in the various setups and network conditions, but the overall delivery probability gets substantially improved compared to that in simple networks. The delivery probabilities of SprayandFocus are much better than other methods with improved overhead ratio and average hop count but at the price of even greater latency; for some scenarios, this will be unacceptably high. Moreover, as the node density increases further, this protocol is unable to achieve its function, which pulls down its overall performance. Comparing all key factors, the KaFiR routing scheme shows a good overall performance, and it balances different factors for various scenarios, which presents a good resilience and tolerance.

In comparison with the one of the latest DTN routing techniques, GT-ACR, the significant improvements for most factors of wireless system performance indicate that mobile subscribers could take advantage of the prediction capability of the KaFiR.

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Chapter 5

KaFiR for UAV aided mobile IoT systems in Smart Cities

5.1 Introduction

5.1.1 Overall

Mobile IoT technology has become one of the most significant emerging paradigms for wireless communications in recent years. Whatever the true position of the progress of IoT into the marketplace [1], there is no doubt that there is considerable and growing demand for ubiquitous communications [2]. The presence of pervasive applications and numerous device features have helped to propel mobile IoT into its highly topical position in wireless communications [3]. Moreover, IoT communication is proposed through the 5G mobile system standards, which are likely to be implemented by 2020 [4], and future smart cities will make substantial use of mobile IoT techniques [5]. This should provide benefits to all citizens from advancements in computer engineering and wireless communications; almost every object developed for human use will be connected to the Internet using mobile IoT technologies.

In the last decade, smart cities have been another rapidly emerging concept [6]. They are defined by the endowment of their infrastructures with more intelligence, which needs a sophisticated and well-designed platform behind each of the services and machines. Therefore, the ubiquitous connectivity of mobile networks has become a substantial necessity of daily life and industry activities. The continued blossoming of ICT produces significantly increasing demands for applications and implementations. Among the cutting-edge technologies, the mobile IoT network plays a key role in supporting the demand to connect all the portable elements involved in smart cities [7]. It lets everything to start talking to everything else, which broadly extends the services in traditional cities and highly improves the life experience of citizens [8].

5.1.2 Challenges

The rapid expansion of the landscape of cities, their growing populations and rapidly increasing number of connected things using various applications and services which increase the conflict of needs and resources. If the current mobile IoT solution is to be widely deployed in smart cities, there are difficulties with this future that either add investment or reduce feasibility. In particular, the lack of infrastructure for traditionally operated mobile networks and the congestion caused by the subscriber density are significant thorny issues.

In [10], Benhamida et al. explain that existing DTN routing protocols are not appropriate for many application domains, and they have to be tailored to Mobile IoT applications in smart cities environments to meet their specific requirements, for instance heterogeneity, substantial amounts of exchanged messages, information-centric based protocols, intermittent connections (ICNs) etc.

5.1.3 Opportunities

Opportunistic radio communication is an alternative approach for mobile IoT systems when there is no operational wireless system or the service is not reliable. In addition, it is of utility when conventional public networks are only suitable for small-scale IoT applications as a result of their high cost in some cases [11]. The majority of wide spread digital elements in mobile IoT networks are connected by RF links, regardless of whether they are stationary objects or mobile things according to the nature of flexible of wireless communication technologies. Most of the applications and services in smart cities borne by the mobile IoT system concentrate on technologies for short-range communication, although some services require long-range communications. The large proportion of the objects in IoT networks generate a small amount of data and information that is only for exchanging the status of the objects, such as location, environment, speed, temperature and so on. Wireless relaying is able to join with these short-range radio links to convert them into long-range connections to transfer this data traffic.

Moreover, decentralized wireless networks can provide the very high degree of resilience needed for the dense interconnection that IoT systems require. The flexibility of UAVs enables rapid and straightforward IoT implementation in scenarios without an infrastructure via decentralized wireless networking, which provides a route to the implementation of wireless IoT networks that overcomes the prerequisite of an existing communication infrastructure [9]. The property of easy and fast UAV implementation makes them highly attractive in many communications applications and facilitates the development of the IoT.

5.1.4 Solutions

The DTN scheme is an opportunistic mobile communication system, in which the end-to-end connectivity is provided between a pair of nodes despite intermittent link connectivity and long variable delays between mobile nodes to help the RF digital data transfer continue on when difficulties of communication occur. Moreover, it can offload the traffic from an operating system to divide unbalanced data flows because many services or applications in IoT smart cities are not time sensitive. The sophisticated mobile network algorithms designed act together to enable SCF communication, despite there being no existing end- to-end path between source and destination [12]. An appropriate protocol is able to accommodate the intermittent connectivity with variable delay, which provides the opportunity for the user information to reach the receiver as required, and the simulation results in the last chapter have demonstrated this.

The DTN provides more network flexibility and resilience [13], therefore, the decentralized wireless network can be one of the solutions for mobile IoT systems. The substantial challenge for applications in IoT systems is the scalability of the wireless network. When the population of things increases, the system needs to maintain the same level of performance as each of the portable things is allowed to make its own determination of how to assist other mobile nodes or the attached system. DTNs have been proposed as UAV communication networking technologies by Motlagh et al. [14]. A network structure for low-altitude UAV-aided information dissemination and data collection for delay tolerant data, and path planning strategies has been presented by Zeng and Zhang [15].

5.2 Principles of Design

The proposed KF packet relaying scheme assumes that all the ground subscribers are fully able to move round the designed wireless coverage territory. The UAVs fly horizontally at a constant altitude and the movement of each ground mobile node and UAV is observable. All of the RF connections established between different portable devices or between a UAV and ground nodes are bi-directional channels. The bandwidth of the bi-directional air channels is adequate to bear the requirements of the applications assumed here. All mobile nodes fully obey the principle of a given relaying scheme as it dictates, which means there are no selfish nodes [4] in the system. For the design of the proposed routing protocol, the strategy guarantees that the system will not cause any bias in any terms. Every subscriber and all data generated by any nodes in the specified radio network are treated equally. The routing protocol designed can be run on each of participating portable smart devices, such as smart phones, tablets, portable sensors, laptops, digital cameras and so on. The proposed scheme presumes that the engaged portable devices and UAVs have sufficient energy, processing capacity and memory space to fulfil their data transmission missions. In spite of the assumptions made before, the design of algorithms has to consider various resources embedded in different terminals and minimize the effect of normal user application and customer feeling. So the occupation of memory, processor capacity, radio bandwidth, and the power consumption have to be optimized and minimized.

In addition, data errors from lower layers will not be considered in the wireless routing protocol designed, as these are assumed to be corrected by the lower layer transmission protocols, such as channel coding, error detection and error correction algorithms.

5.3 Aims of Protocol

The protocol proposed in chapter 4 is a wireless communication solution to address the difficulties when mobile systems have problems in satisfying information exchange needs, particularly in extreme natural disaster circumstances such as earthquake or tsunami. Given the lack of infrastructure or frequency spectrum in such scenarios, it is not possible to reliably obtain end-to-end resources between sources and destinations, causing unpredictable, long propagation delays between nodes. The protocol is not designed to fulfil the needs of real-time services, for instance, voice calls or video calls. All of the information generated by the subscribers will be executed as data packets and relayed through the wireless network to reach its receivers, as long as the next appropriate hop is present, so the resilience and tolerance of the relaying system have to be considered.

Due to the freedom of movement of the mobile users, portable nodes can join or leave the mobile network at any time and wireless system scalability is one of the essential challenges. Meanwhile, the freedom of mobile subscribers also causes uncertainties for the RF system, including in the air link between adjacent nodes and in the location of message destination nodes. The network pattern and topology change significantly with time. The protocol needs to address these challenges and uncertainties to improve the overall system performance.

5.4 Tracking Strategies

Each mobile subscriber is able to move about the radio coverage territory freely, whilst the UAVs keep their flying trajectories over the service area. As stated in Section 5.2, the low altitude UAVs fly horizontally at a constant altitude. The trajectory of each UAV can be mapped onto the land, which it covers as a two dimensional movement path. The motion of the UAV can then be processed as a ground mobile node in the mathematical model. The movement of each node is a random motion so that the collective movement of all the wireless nodes forms a stochastic system. In mathematical or statistical terms, this is a random walk of subscribers described via a stochastic process. This random walk is observable for the portable terminals; their locations velocities and accelerations (or decelerations) can be observed but the observations could be different from the true states of the targeted objects. This information is defined as two types of data: (a) The unknown real state of the targeted portable device, denoted by X; (b) the observed or measured behavior data of the particular wireless subscriber, denoted by Y. The unknown data of X are computable by the appropriate mathematical and statistical theories based on the observation or measurement data of Y, which is a type of reasoning or tracking. The proposed statistical methods are used to accomplish the moving object motion tracking operation by using a classical Bayesian statistical approach [16].

These potentially computationally burdensome tasks, such as algorithm computation and historical data storage, need to be performed by each individual subscriber’s mobile device, such as smartphones, tablets, e-book readers, portable handsets and laptops. The outcomes need to be propagated wirelessly. Each mobile device will have its own limitations on processing capacity, embedded storage memory and particularly wireless bandwidth. Thus, the computerized algorithms need to be simplified and utilized on a minimized scale, which is within mobile device capabilities including the available wireless link bandwidth. Each mobile node only needs to track and predict nodes that can establish direct bi-directional radio connections between the two adjacent nodes. The prediction information is only exchanged among these neighbouring mobile nodes. Thus, for prediction, each mobile node needs to obtain it neighbour node state information nodes by movement tracking.

The moving objects tracking or reasoning process is a series of filtering, prediction and smoothing operations based on Bayesian inference. The particular mathematical model employed here for tracking the moving targets is the KF algorithm, which a classical linear Gaussian optimal prediction and tracking algorithm [17].

The tracking and prediction solution is to estimate the states of moving targets (here these are the mobile subscribers that could be stationary or movable targets) based on the measurement information, and then to infer the movement states in the next coming moment via statistical algorithms. The state of the tracked objects can be seen as belonging to a dynamical system [18] and the states are independent of the time, creating an autonomous system. For each particular interval, every individual wireless user has its own set of state data in a state space model to indicate its state space information [19]. This set of data is denoted as a vector of the state space identification. A series of state vectors are used to represent the trace path of a particular portable device or a predefined wireless user group within the wireless network. The trajectories of targeted mobile nodes have a continuous appearance but the measuring nodes take the measurement data in each constant interval (or according to a preset fixed sampling frequency) making the measurement data discrete. As in the previous chapter this is the continuous – discrete filtering mode [19], and the observation outcomes are in the discrete mode that will be the state space information input. The observation data could contain one or all of position, velocity, acceleration/deceleration, etc. In this work the estimated state is only limited to the position of mobile subscriber nodes.

5.5 Simulation Results

Using the ONE simulator, the algorithm was tested in a range of scenarios to obtain comprehensive performance results for the new protocol. The general parameters for the simulation configurations are specified in Table 5-1.

In this chapter, the proposed routing protocol will be compared with PRoPHET relaying scheme as one of candidates first time, because PRoPHET does not deliver a sequence of proper results for the parameter setup in previous chapters. PRoPHET relaying strategy uses encounter history with other portable node to determine the probability for a certain node to deliver the packet to its destination. If one node has just encountered with the destination node and moving away from it, which does not mean that this node will encounter the destination again shortly.

TABLE 5-1 PARAMETERS OF SIMULATION CONFIGURATIONS

Parameters	**Value of parameters**
Buffer Size (MB)	15
Message Time To Live (TTL) (minute)	60, 100, 150, 200, 250
Message Interval (second)	5-15, 15-25, 25-35, 35-45, 45-55, 55-65, 65-75
Message Size (MB)	0.005-0.01, 0.01-0.02, 0.1-0.2, 0.3-0.5, 0.5-1, 2.5-3.0, 4.5-5.0
Total Number of Nodes	66, 96, 126, 156, 231, 306, 456, 606
Simulation Time (second)	86400
Protocol	Epidemic, KaFiR, PRoPHET, Spray and Wait (Binary version)

The following parameters compared the different aspects regarding the different network scenarios.

5.5.1 Message Interval

Different message intervals simulated the various message generation rates from the source nodes which need to have data relayed across the UAV assisted DTN IoT system. All four different routing protocols were tested using seven different message interval ranges. The message generation rate is inversely proportional to the message interval.

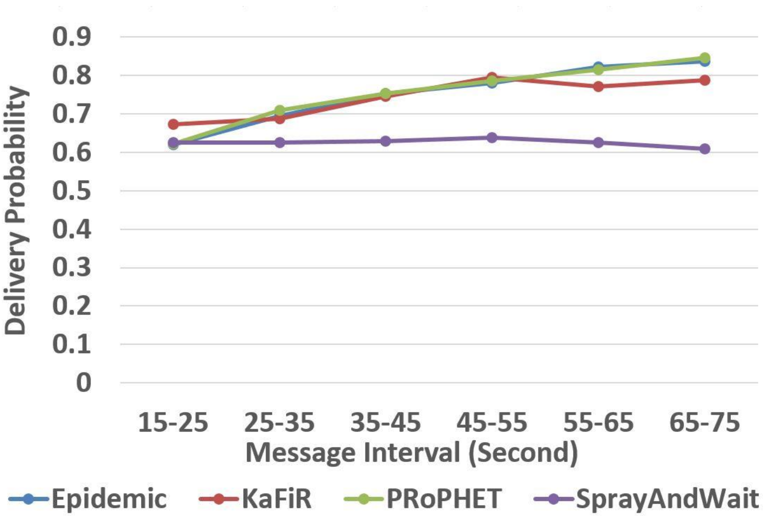

Fig. 5-1 Delivery Probability vs. Message Interval.

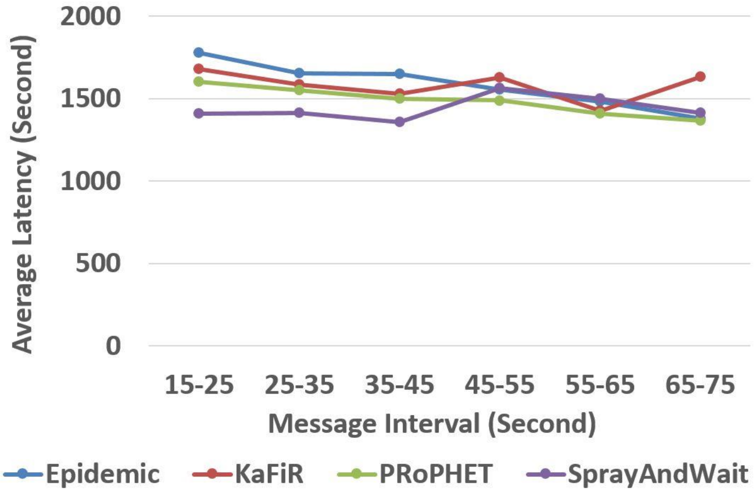

Fig. 5-2 Average Latency vs. Message Interval.

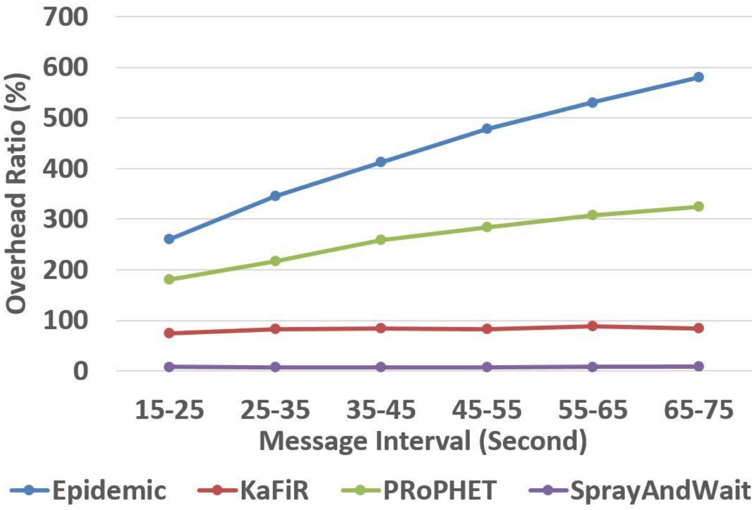

Fig. 5-3 Overhead Ratio vs. Message Interval.

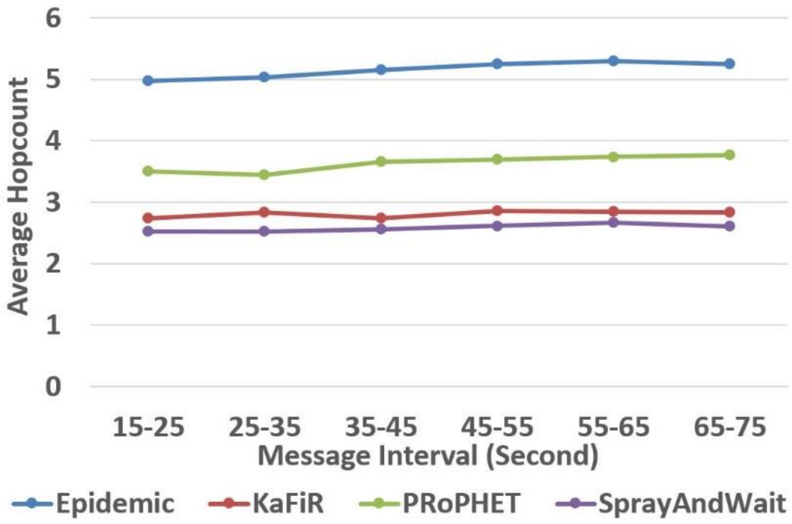

Fig. 5-4 Average Hopcount vs. Message Interval.

Fig. 5-1 indicates that when the source nodes generate messages less frequently, the delivery probabilities of Epidemic, KaFiR and PRoPHET increase gently and are higher than SprayAndWait at all message rates. The increasing curve of KaFiR is comparable to the performance of Epidemic and PRoPHET, showing that it possesses robustness to the variation in message intervals. Fig. 5-2 presents the average latency for all the schemes investigated and shows that they all perform well as the message interval varies, remaining in a relatively a narrow band around 1500 seconds.

Fig. 5-3 and Fig. 5-4 show that only KaFiR and SprayAndWait offer good performance for overhead ratio and average hop count as the message interval changes. Recalling Fig. 5-1, it may be seen that SprayAndWait's performance in terms of overhead ratio and average hop count is bought at the cost of reduced delivery probability. KaFiR enables an extra 12% of the packets to be delivered in this most important of categories.

5.5.2 Message Time To Live (TTL)

In Fig. 5-5, the KaFiR protocol exhibits a slowly declining delivery rate against TTL and the overall performance is much better than Epidemic and PRoPHET. Only SprayAndWait increases the delivery probability when the message TTL gets high, which implies it more relies on a longer TTL. A long message TTL requires the intermediate nodes to store and carry messages for a long time, which could cause buffer overflow for relaying nodes. There are not many differences in average latency between the protocols tested when message TTL changes as Fig. 5-6 shows.

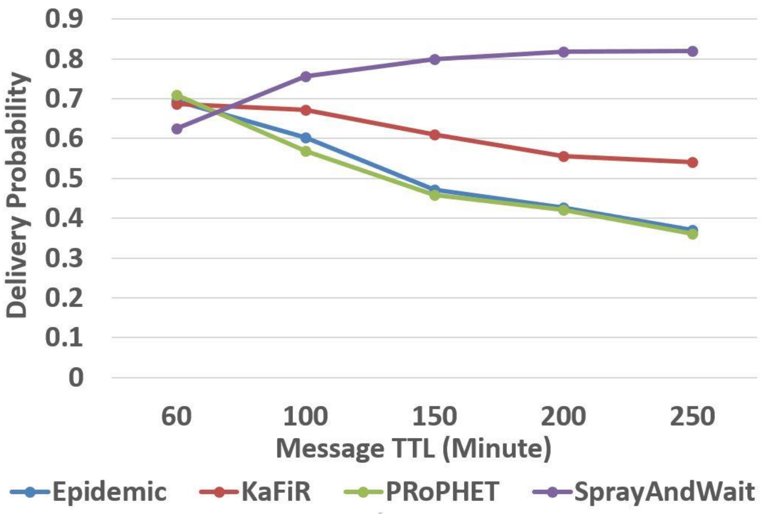

Fig. 5-5 Delivery Probability vs. Message TTL.

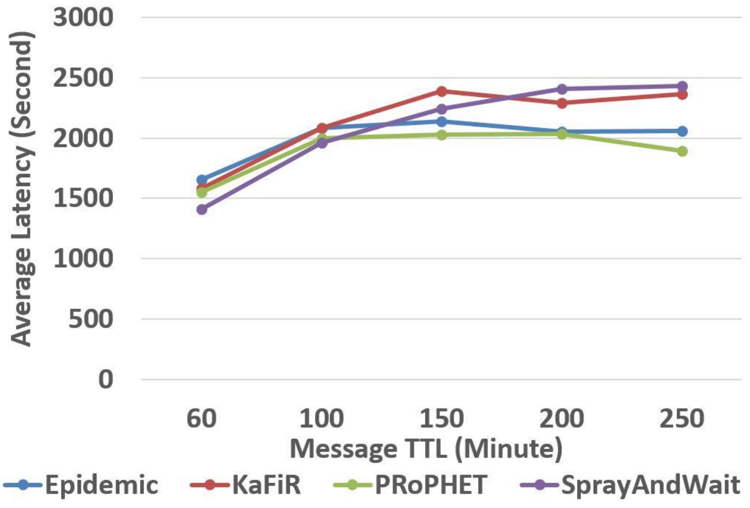

Fig. 5-6 Average Latency vs. Message TTL.

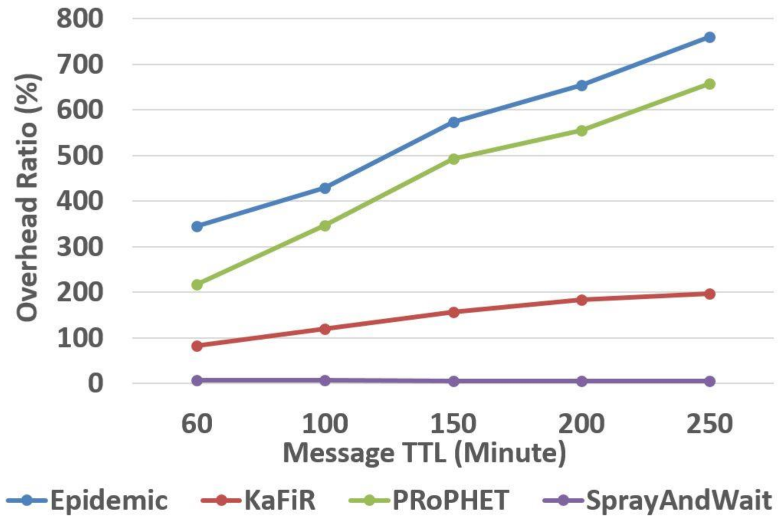

Fig. 5-7 Overhead Ratio vs. Message TTL.

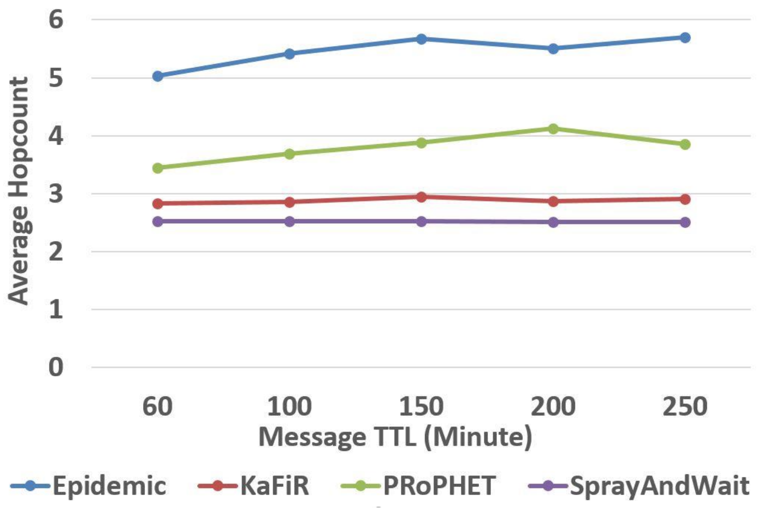

Fig. 5-8 Average Hopcount vs. Message TTL.

With respect to overhead ratio and average hop count, Fig. 5-7 and Fig. 5-8 show that KaFiR and SprayAndWait keep these relatively low. The latter has a small advantage in both indicators.

Message TTL defines the freshness of relaying messages. The average buffer time can further reveal the store and carry process between source and destination nodes. Fig. 5-9 gives the detailed average buffer time of KaFiR and SprayAndWait, the two best performing relaying protocols. It may be seen that the average buffer time for SprayAndWait is almost seven times higher than KaFiR.

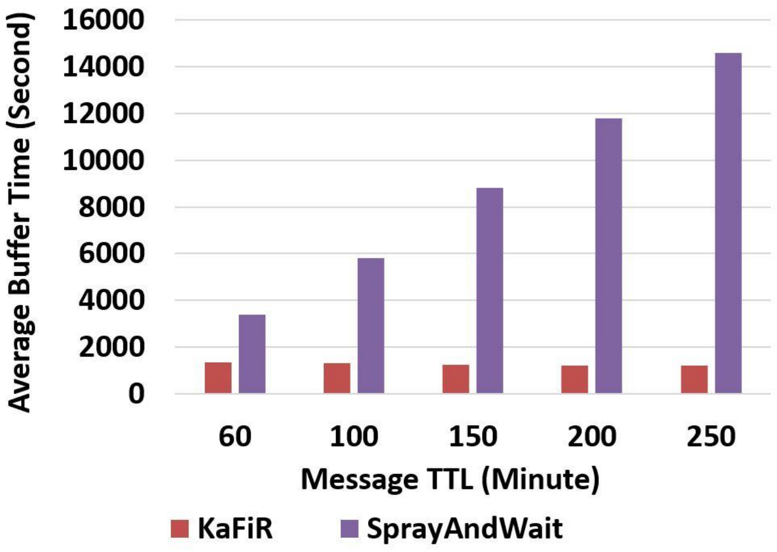

Fig. 5-9 Average Buffer Time vs. Message TTL.

5.5.3 Total Number of Nodes

In Fig. 5-10 it is shown that KaFiR presents a very good trend when the total number of nodes in a DTN IoT system grows, as the delivery probability increases steadily. SprayAndWait does not change much with increasing node numbers; it actually begins to decrease when the network density becomes high. ProPHET and Epidemic routing show some improvements with node density but do not generally exceed the performance of KaFiR. KaFiR is also the best protocol in terms of decreasing latency with increased node numbers as shown in Fig. 5-11.

In terms of overhead and hop count, KaFiR exhibits a gentle increase when number of nodes grows as may be seen in Fig. 5-12 and Fig. 5-13. This is much better than Epidemic and PRoPHET but a little more than SprayAndWait, whose performance is essential constant in these parameters. It may also be noted from Fig. 5-13 that KaFiR delivers the lowest average hopcount control when the network in sparse.

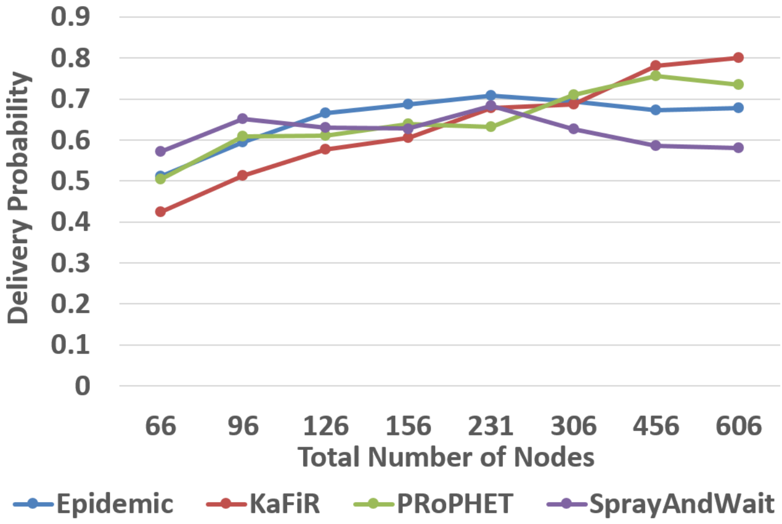

Fig. 5-10 Delivery Probability vs. Total Number of Nodes.

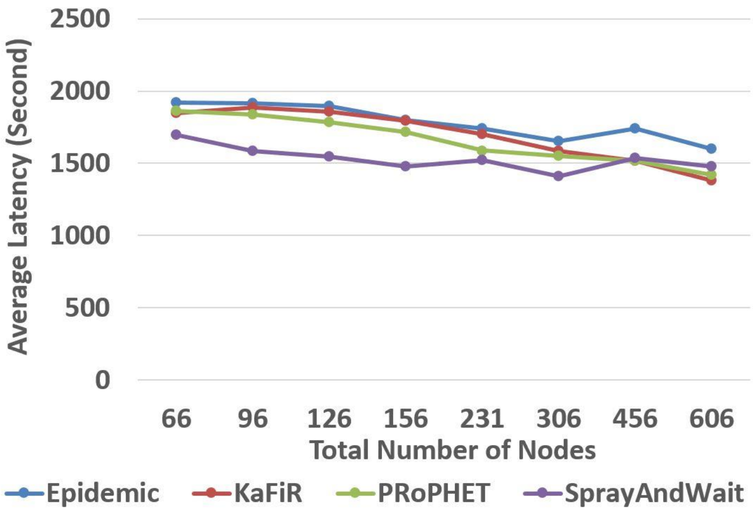

Fig. 5-11 Average Latency vs. Total Number of Nodes.

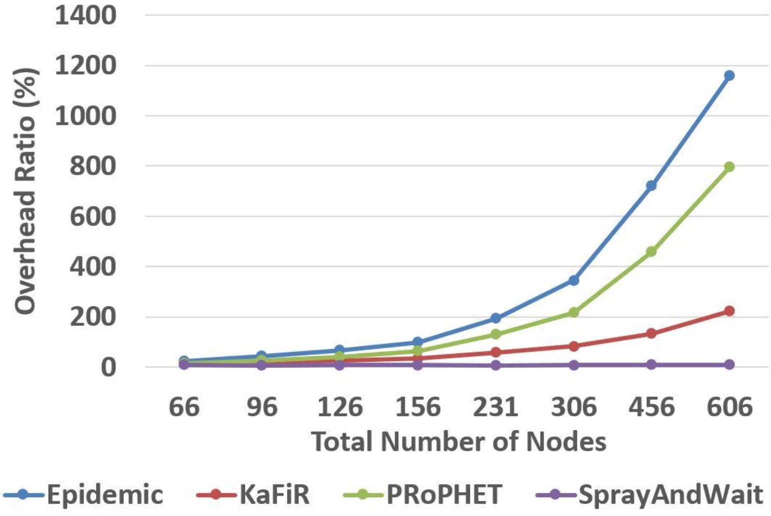

Fig. 5-12 Overhead Ratio vs. Total Number of Nodes.

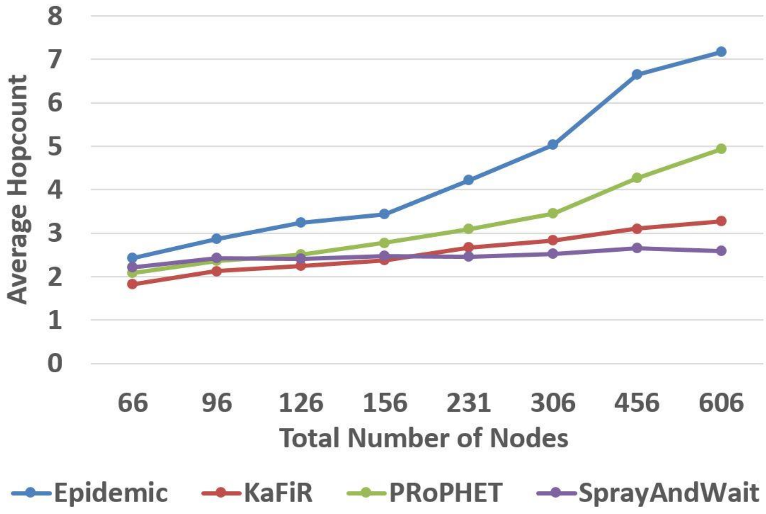

Fig.5-13 Average Hopcount vs. Total Number of Nodes.

Thus, KaFiR delivers the best performance in terms of scalability, which is a key property in a DTN IoT system. While the total number of mobile nodes reaches 606, KaFiR presents the highest delivery probability and low average latency among all protocols. At the same time, its overhead ratio and average hop count remain well controlled.

5.5.4 Message Size

The information borne by IoT networks comprises location updates, status data or collected numerical messages, which can be encapsulated into small data frames and the message size is only a few kB, therefore, the message transferred in mobile IoT network normally has limited package size [20]. In [21], Meiling et al. give the example of the frame size of IEEE 802.15.4, which is up to 127 bytes.

Fig. 5-14 shows that the delivery probability of KaFiR protocol has a very stable performance as the message size changes, and the delivery ratio is always higher than 80%. SprayAnd Wait has the same pattern, but the value is lower than 70%. Although Epidemic performs well when the message size is small, it has the same delivery probability with PRoPHET and KaFiR, when the message size is 400-500 kB.

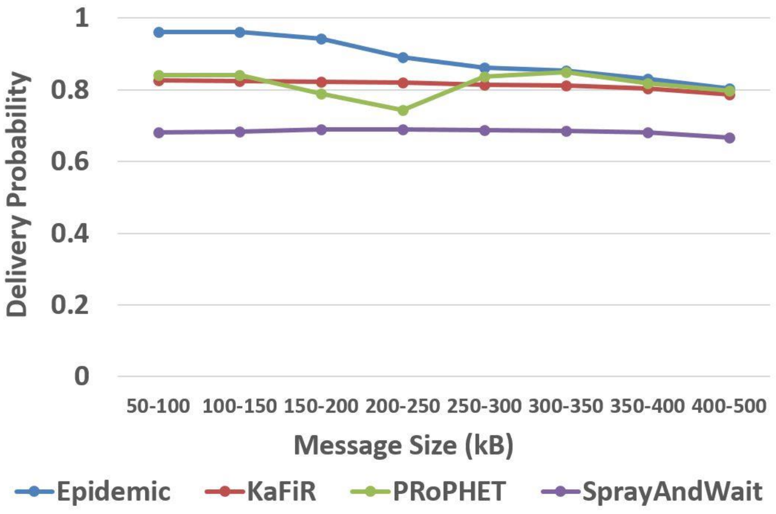

Fig.5-14 Delivery Probability vs. Message Size.

In Fig. 5-15, Fig. 5-16 and Fig. 5-17, KaFiR and SprayAndWait manage to maintain stable performance regarding average latency, overhead ratio and average hopcount. For these three evaluation metrics, Epidemic does not present as good a performance as its delivery probability. This is especially true for overhead ratio and average hopcount, which are much higher value than other protocols. PRoPHET has a moderate performance, with its best feature being the relatively low latency.

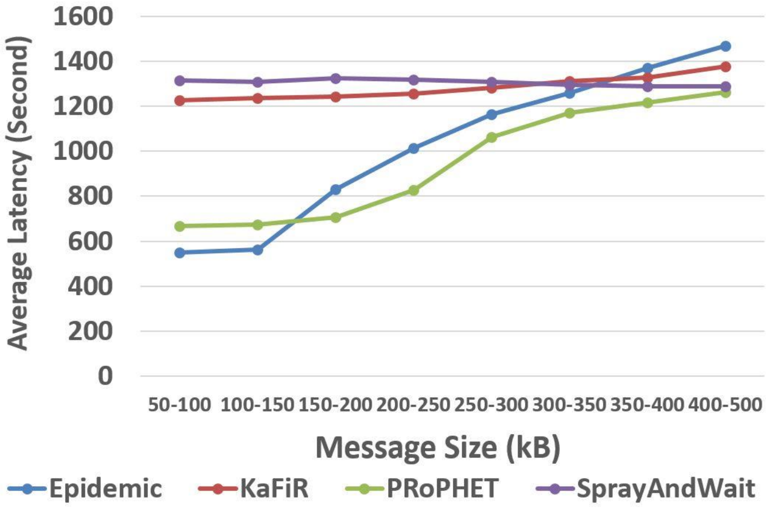

Fig. 5-15 Average Latency vs. Message Size.

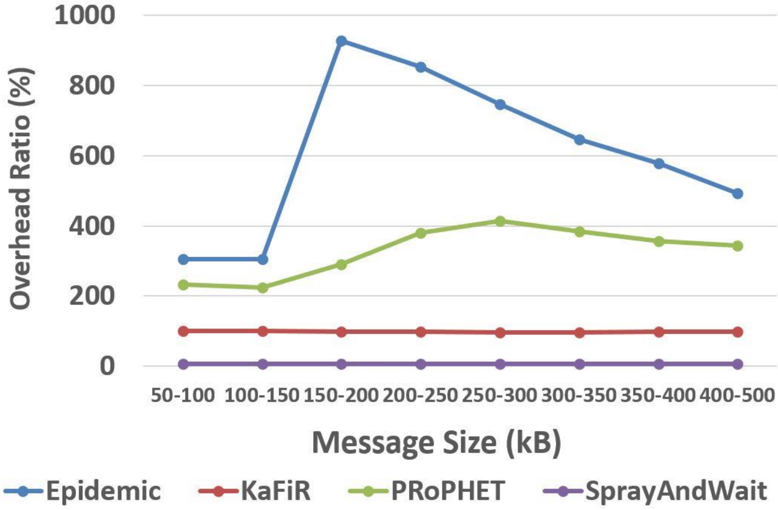

Fig. 5-16 Overhead Ratio vs. Message Size.

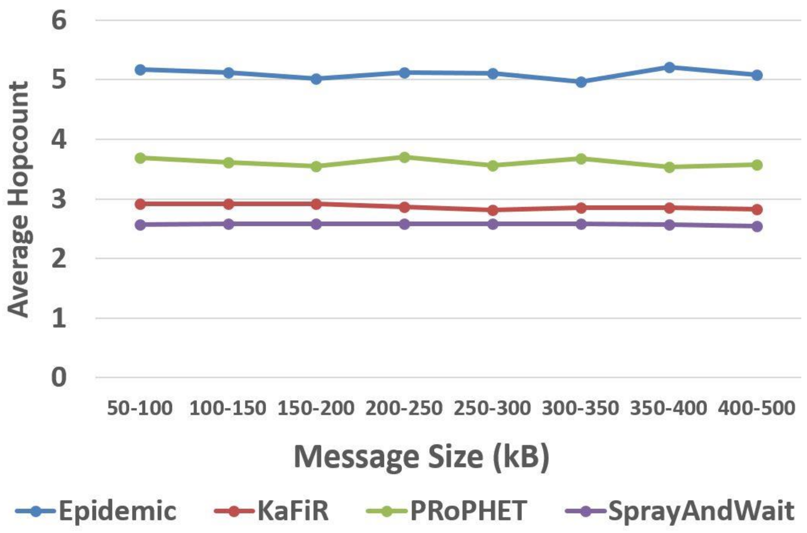

Fig.5-17 Average Hopcount vs. Message Size.

In practice, mobile IoT needs to maintain a stable performance in spite of the change of relaying message size. Regarding the overall performance comparison of all candidate DTN routing protocols, the proposed KaFiR relaying algorithm is highly suitable for IoT applications and services in smart cities.

5.6 Summary

With regard to the three key aspects to evaluate the performance of DTN IoT routing protocols presented above, KaFiR presents excellent scalability, resilience and tolerance. As the message generation rate and TTL vary, KaFiR shows competitive changes in delivery probability, which increases significant as the node population grows. KaFiR shows only a small fluctuation for varying network conditions, which make it easy for a system developer to fulfil applications in different scenarios. The reduced overhead ratio and average hop count of KaFiR can make the network more efficient and save more energy for portable terminals.

The SprayAndWait scheme delivers the best performance in controlling overhead and hop count but KaFiR offers similar delivery probability which is the most important for the protocol estimation. Moreover, the performance of SprayAndWait comes with a high average buffer time. The average latency and hop count outcomes of Epidemic routing and PRoPHET are poor in comparison, making them less appropriate relaying schemes for DTN IoT network applications.

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Chapter 6

PaFiR --- Particle Filter Routing Scheme

6.1 Introduction

6.1.1 Background

Increasing urbanization means that smart cities should provide more and more functions to benefit their citizens by relying on the substantial data processing and exchange capabilities now possible. Cities sizes are constantly increasing so that the population living in urban territories is anticipated to double by 2050 [1]. In consequence, the number of IoT devices in smart cities will grow exponentially. Although it is difficult to predict the numbers precisely, the total sum of Internet-connected things is most likely to be between 25 billion to 50 billion by 2020. This can generate significant unpredictable and unbalanced data loads for the bearing IoT network to support the consequent application and service demands. Therefore, for the citizens to enjoy the benefits from ubiquitous networking, the traffic-bearing infrastructure of smart cities will face more and more challenges on its resources in high density smart cities. In particular: limited RF spectrum; radio signal coverage and blind spots; extremely high density of wireless network subscribers; network congestion caused by unbalanced or bursty data; mobile site acquisition; electromagnetic interference. Furthermore, natural disasters (hurricanes, thunderstorms, earthquakes and tsunamis) or unpredictable incidents (power cuts, system failures, fire accidents, hacker or terrorist attacks and sabotage) are potential risks that make the communication system vulnerable and ubiquitous access extremely challenging. A backup solution could alleviate these problems; however, the degree and scale of the solution is complex, and even a small-scale of solution could result in an extremely high cost for some complex cases in such a super smart city. In this chapter, a sophisticated algorithm is required to design an enhanced solution to adapt to these changes and to be easy to deploy.

6.1.2 Challenges

As the flexibility of the UAVs can achieve the fast implementation of DTN systems, Motlagh et al. proposed a low altitude UAV-based solution for IoT services [2] that can be applied as a solution to assist data packet relaying.

Considering the expansion of mobile IoT systems in smart cities, a large population of portable devices will attach to the network in the air and on the ground. The motions of UAVs and ground moving elements are dramatically diversified. The motion status changes of some mobile IoT subscribers and intermediate relaying UAVs happen much more frequently than the scenarios mentioned in Chapter 5, moreover, instantaneous velocity and acceleration (or deceleration) variations shift cannot be examined as a linear process any more. Based on the Bayesian estimation approach [3], this type of movement change of the state space of portable IoT nodes leads to their classification as maneuvering objects with the behavioural characteristics of such objects. When the population of maneuvering objects is large, or the degree of maneuvering is high, the classical Bayesian inferencing method given by Gelman et al. [3] is no long appropriate, so the KaFiR routing protocol proposed in Chapter 5 needs to be improved to be suitable for these more complex scenarios. A more rigorous object tracking and prediction Bayesian filtering algorithm is required to tackle the maneuvering mode [4].

In this chapter, an enhanced wireless routing scheme will be proposed using the PF algorithm to empower portable smart devices with intelligent capacities for the radio communication system by applying online nonlinear and non-Gaussian Bayesian tracking [5]. The proposed routing protocol facilitates the offloading of traffic from traditional wireless networks and enables the IoT system to adopt UAVs to assist in special or urgent circumstances. This offers the network increased scalability, tolerance and resilience, to achieve the goal of smart relaying.

6.2 Particle Filter

The Particle filter (PF), also known as the Sequential Monte Carlo (SMC) method [6], is a statistical filtering method based on Monte Carlo method and recursive Bayesian estimation [7]. It uses the Monte Carlo method to solve the integral operation of Bayesian estimation based on the Bernoulli Law of large numbers and the central limit theorem in probability theory. When a problem is repeated infinitely many times, the suboptimal solution that is closest to the correct result, and the frequency of occurrence of time is used to replace the probability of occurrence of an event. [8]

The PF algorithm generates a set of random samples in the state space according to the empirical condition distribution of the system state vector, and then continuously adjusts the weight and position of the particles to correct the initial empirical condition distribution by adjusting the information of the particles. When the sample size is large, the Monte Carlo method can formulate a distribution that is similar to the real posterior probability density function of the state variable. Here, samples are the particles that can be understood as estimators. The PF is applicable to any non-Gaussian and nonlinear stochastic system that can be represented by a state space model. [9]

Thus, the PF breaks through the traditional Kalman filtering theory framework and has no restrictions on process noise and measurement noise of the system. It can be applied to any nonlinear system and the accuracy can approximate the optimal estimation, which is a very effective nonlinear filtering technology. As the increasing capability of portable terminals and improvements of algorithm optimization, the PF can be widely applied in smart devices.

6.2.1 Bayesian Filtering

It is first supposed that there is a system with state and measurement equations as follows:

$$x_k = f_k(x_{k-1}, v_{k-1}) \tag{6 – 1}$$

$$y_k = h_k(x_k, n_k) \tag{6 – 2}$$

where x is the system state, y is the measured data, f and h are respectively the state transfer function and the measurement function, v and n are respectively the process noise and the measurement noise, and the noise is independent and identically distributed.

From the Bayesian theory point of view, the state estimation problem, such as target tracking, is based on a series of existing data (posterior knowledge), $y_{1:k}$, and a recursively calculated current state of probability, x_k. This probability is the distribution $p(x_k|y_{1:k})$ that requires recursive calculations by predicting and updating steps.

The prediction process uses the system model in state Equation (6 – 1) to predict the prior probability density of the state, that is to estimate the state in the next moment through the existing prior knowledge $p(x_k|x_{k-1})$. The update process uses the latest measured values to correct the prior probability density to obtain the posterior probability density, which is to correct the previous estimation. [10]

To solve these problems, it is generally assumed that the state transition of the system obeys a first-order Markov model [11], in which the state of the current instant x_k is only related to the state in the previous instant, x_{k-1}. At the same time, it is assumed that the data y_k measured at time k are only related to the current state x_k, as it is shown in Equation (6 – 2) above. To perform the recursion process, the known probability density function at instant $k-1$ is defined as $p(x_{k-1}|y_{1:k-1})$.

The prediction process is: the current state $p(x_k|y_{1:k-1})$ can be obtained from the probability density of the previous moment $p(x_{k-1}|y_{1:k-1})$, which implies that the state probability occurring in the next instant x_k can be predicted by the measurement data at the previous instants 1 to $k-1$:

$$\begin{aligned} p(x_k|y_{1:k-1}) &= \int p(x_k, x_{k-1}|y_{1:k-1})\, dx_{k-1} \\ &= \int p(x_k|x_{k-1}, y_{1:k-1})\, p(x_{k-1}|y_{1:k-1}) dx_{k-1} \\ &= \int p(x_k|x_{k-1})\, p(x_{k-1}|y_{1:k-1}) dx_{k-1} \quad . \qquad (6-3) \end{aligned}$$

In equation (6 – 3), the first line to the second line are the application of the Bayesian formula. The third line follows from the second because of the assumption of a first-order Markov process, the state x_k is only determined by x_{k-1}.

The prediction process is: the posterior probability $p(x_k|y_{1:k})$ is from $p(x_k|y_{1:k-1})$. The last step is only prediction. Here, there are more measurements at time k. Correcting the above prediction is the smoothing process. The posterior probability here will also be substituted into the next prediction as the prior, forming a recursion:

$$\begin{aligned} p(x_k|y_{1:k}) &= \frac{p(y_k|x_k, y_{1:k-1}) p(x_k|y_{1:k-1})}{p(y_k|y_{1:k-1})} \\ &= \frac{p(y_k|x_k) p(x_k|y_{1:k-1})}{p(y_k|y_{1:k-1})} \qquad (6-4) \end{aligned}$$

where, normalization constant is [12]:

$$p(y_k|y_{1:k-1}) = \int p(y_k|x_k)\, p(x_k|y_{1:k-1}) dx_k \quad . \qquad (6-5)$$

The first line to the second line of the equation is because the measurement equation knows that y_k is only related to x_k, $p(y_k|x_k)$ is called the likelihood function, which is determined by the measurement equation. $y_k = h_k(x_k) + n_k$, x_k is a constant. Also, $p(y_k|x_k)$ is only related to the probability distribution of the measured noise n_k. This provides a programming basis for the sampling of the weights in the SIR (Sequential Importance Resampling) PF [13].

The integral operation is needed in the above derivation process. For a nonlinear and non-Gaussian system, it is difficult to obtain an analytical solution of the posterior probability. To solve this problem, Monte Carlo sampling has to be introduced.

6.2.2 Monte Carlo Sampling

To estimate the expected value of functions of probability distribution $p(x)$, a series of samples (particles) acquired from a probability distribution can be used. For Example:

$$E(f(x)) = \int_a^b f(x)p(x)dx$$

$$Var(f(x)) = E(f(x) - E(f(x)))^2 = \int_a^b (f(x) - E(f(x)))^2 p(x)dx \qquad (6-6)$$

The idea of Monte Carlo sampling is to use the empirical mean value to substitute for the integral operation:

$$E(f(x)) \approx \frac{f(x_1)+\cdots+f(x_N)}{N} \qquad (6-7)$$

This is based on the Law of large numbers, so if the number of samples N is large enough, the above formula approximates the expected value. The method of estimating the probability is to achieve the expected probability by the Monte Carlo method.

In Section 6.2.1, the integral operation is used in the calculation of Bayesian posterior probability. To solve the difficult integral, Monte Carlo sampling can be used instead of calculating the posterior probability.

Assuming that N samples can be acquired from the posterior probability, the calculation of this can be expressed as:

$$\hat{p}(x_k|y_{1:k}) = \frac{1}{N}\sum_{i=1}^{N} \delta\left(x_k - x_k^{(i)}\right) \approx p(x_k|y_{1:k}) \qquad (6-8)$$

where, $f(x) = \delta(x_k - x_k^{(i)})$ is the Dirac delta function [14].

For object tracking, it is necessary to acquire the expected value of the movement current state that is the meaning of filtering.

$$E(f(x_k)) \approx \int f(x_k)\hat{p}(x_k|y_{1:k})dx_k$$

$$= \frac{1}{N}\sum_{i=1}^{N} \int f(x_k)\delta(x_k - x_k^{(i)})dx_k$$

$$= \frac{1}{N}\sum_{i=1}^{N} f(x_k^{(i)}) \qquad (6-9)$$

The average of state values of these sampled particles is the expected value that is the filtered value, where $f(x)$ is the state function of each particle, which is the process of particle filtering. As long as a sufficient large number of particles can be sampled from the posterior probability, the results are the estimation of their real states. However, the problem is the unknown posterior probability and how to obtain samples from the posterior probability distribution; importance sampling is the method to solve this problem.

6.2.3 Importance Sampling

To solve the problem of the infeasibility of sampling from the target distribution $p(x|y_{1:k})$, importance sampling introduced by Liu [15] [16] is applied using an approximate distribution called the importance distribution $q(x|y_{1:k})$ to draw samples. Thus, the expectation problem becomes:

$$
\begin{aligned}
E(f(x_k)) &= \int f(x_k)\frac{p(x_k|y_{1:k})}{q(x_k|y_{1:k})}q(x_k|y_{1:k})dx_k \\
&= \int f(x_k)\frac{p(y_{1:k}|x_k)p(x_k)}{p(y_{1:k})q(x_{k|}y_{1:k})}q(x_k|y_{1:k})dx_k \\
&= \int f(x_k)\frac{W_k(x_k)}{p(y_{1:k})}q(x_k|y_{1:k})dx_k \qquad (6-10)
\end{aligned}
$$

where,

$$W_k(x_k) = \frac{p(y_{1:k})p(x_k)}{q(x_k|y_{1:k})} \propto \frac{p(x_k|y_{1:k})}{q(x_k|y_{1:k})} \quad .$$

Due to:

$$p(y_{1:k}) = \int p(y_{1:k}|x_k)p(x_k)dx_k$$

Thus, equation (6 – 10) can be reformed as:

$$
\begin{aligned}
E(f(x_k)) &= \frac{1}{p(y_{1:k})}\int f(x_k)W_k(x_k)q(x_k|y_{1:k})dx_k \\
&= \frac{\int f(x_k)W_k(x_k)q(x_k|y_{1:k})dx_k}{\int p(y_{1:k}|x_k)p(x_k)dx_k} \\
&= \frac{\int f(x_k)W_k(x_k)q(x_k|y_{1:k})dx_k}{\int W_k(x_k)q(x_k|y_{1:k})dx_k}
\end{aligned}
$$

$$= \frac{E_{q(x_k|y_{1:k})}(W_k(x_k)f(x_k))}{E_{q(x_k|y_{1:k})}(W_k(x_k))} \quad . \qquad (6-11)$$

The above expectation calculation can be solved by the Monte Carlo method by sampling N samples

$$\left\{x_k^{(i)}\right\} \sim \mathrm{q}(x_k|y_{1:k})$$

then, using the average of the samples to estimate expectations, equation (6 – 11) can be approximated as:

$$E\big(f(x_k)\big) \approx \frac{\frac{1}{N}\sum_{i=1}^{N} W_k(x_k^{(i)})f(x_k^{(i)})}{\frac{1}{N}\sum_{i=1}^{N} W_k(x_k^{(i)})}$$

$$= \sum_{i=1}^{N} \widetilde{W}_k(x_k^{(i)})f(x_k^{(i)}) \qquad (6-12)$$

where,

$$\widetilde{W}_k\left(x_k^{(i)}\right) = \frac{W_k(x_k^{(i)})}{\sum_{i=1}^{N} W_k(x_k^{(i)})} \quad .$$

This is the weight after normalization, and the weight in equation (6 – 10) is without normalization. The formula (6 – 12) is the form with weighted sum, which is not the mean of all the particle states as it presents in equation (6 – 2), and different particles have their corresponding weights. If the weight of the particles is significant, it means that they are more reliable.

The problem of posterior probability sampling has been solved as above, however, the calculation method of weight of each particle is inefficient, as $p(x_k|y_{1:k})$ has to be recalculated for every additional sample, and it is complicated to do the calculation by this formula. To avoid calculating $p(x_k|y_{1:k})$, the best method is to calculate weights in a recursive way, which is called Sequential Importance Sampling (SIS) that is the prototype of particle filtering.

For the derivation of weight W in recursive form, here, assuming the importance probability density function is $q(x_{0:k}|y_{1:k})$, where the subscript of x is $0{:}k$, that is, PF is a posteriori that estimates the state of all past moments, and it can be broken down into:

$$q(x_{0:k}|y_{1:k}) = q(x_{0:k-1}|y_{1:k-1})q(x_k|x_{0:k-1}, y_{1:k}) \quad .$$

The recursive form of the posterior probability density function is:

$$\begin{aligned} p(x_{0:k}|Y_k) &= \frac{p(y_k|x_{0:k}, Y_{k-1})p(x_{0:k}|Y_{k-1})}{p(y_k|Y_{k-1})} \\ &= \frac{p(y_k|x_{0:k}, Y_{k-1})p(x_k|x_{0:k-1}, Y_{k-1})p(x_{0:k-1}|Y_{k-1})}{p(y_k|Y_{k-1})} \\ &= \frac{p(y_k|x_k)p(x_k|x_{k-1})p(x_{0:k-1}|Y_{k-1})}{p(y_k|Y_{k-1})} \qquad (6-13) \\ &\propto p(y_k|x_k)p(x_k|x_{k-1})p(x_{0:k-1}|Y_{k-1}) \end{aligned}$$

where, Y_k is the simplified form of $y_{1:k}$. Equation (6 – 13) is the same as the derivation of the posterior probability in the Bayesian filter, except that x_k becomes $x_{0:k}$ with the result that although the Bayesian estimation needs the integral operation, the decomposition of the posterior probability does not.

The recursive form of the particle weight is:

$$\begin{aligned} W_k^{(i)} &\propto \frac{p\left(x_{0:k}^{(i)}\middle|Y_k\right)}{q\left(x_{0:k}^{(i)}\middle|Y_k\right)} \\ &= \frac{p\left(y_k\middle|x_k^{(i)}\right)p\left(x_k^{(i)}\middle|x_{k-1}^{(i)}\right)p\left(x_{0:k-1}^{(i)}\middle|Y_{k-1}\right)}{q\left(x_k^{(i)}\middle|x_{0:k-1}^{(i)}, Y_k\right)q\left(x_{0:k-1}^{(i)}\middle|Y_{k-1}\right)} \qquad (6-14) \\ &= W_{k-1}^{(i)} \frac{p\left(y_k\middle|x_k^{(i)}\right)p\left(x_k^{(i)}\middle|x_{k-1}^{(i)}\right)}{q\left(x_k^{(i)}\middle|x_{0:k-1}^{(i)}, Y_k\right)} \quad . \qquad (6-15) \end{aligned}$$

This derivation of the weighted recursive form is derived in Equation (6 – 10) that has no normalization. The formula for state estimation is

$$\sum_{i=1}^{N} \widetilde{W}_k(x_k^{(i)})f(x_k^{(i)})$$

so that the weight is normalized. Therefore, in practical applications, after the recursion process of W_k , the normalization is required to be substituted into Equation (6 – 12) to calculate the expected value. The SIS Filter is required once the weights are available [17].

6.2.4 Sequential Importance Sampling Filter

The importance distribution function q is assumed to be:

$$q(x_k|x_{0:k-1}, y_{1:k}) = q(x_k|x_{k-1}, y_k) \qquad (6-16)$$

which means the importance distribution is only related to the state in the previous instant x_{k-1} and the measurement y_k, then Equation (6 – 14) can be converted into:

$$W_k^{(i)} \propto W_{k-1}^{(i)} \frac{p\left(y_k \middle| x_k^{(i)}\right) p\left(x_k^{(i)} \middle| x_{k-1}^{(i)}\right)}{q\left(x_k^{(i)} \middle| x_{k-1}^{(i)}, y_k\right)} \qquad (6-17)$$

that is the PF filtering algorithm which is based on the former assumptions, and the SIS filter to solve the problem of that the posterior probability cannot be sampled. In fact, there are many classic methods for sampling from a posteriori probability, that is, how to generate a sample with a specific probability density, such as, rejection sampling [18], Markov Chain Monte Carlo (MCMC) [19], Metropolis-Hastings algorithm [20] [21], Gibbs sampling [22]. However, there are still some practical issues in the applications, such as, the degeneracy problem [23], which needs the solution of resampling.

The degeneracy problem in SIS filtering is that the weight of many particles becomes very small, and can even be neglected, after a few iterations. Only a few particles have relatively large weights. The variance of the particle weight increases with time, and the number of effective particles in the state space is small. As the number of invalid sampling particles increases, a large amount of computation is wasted on particles that have little effect on the estimated posterior filtering probability distribution which results a decreased estimation performance, this is illustrated in Fig. 6-1 and Fig. 6-2.

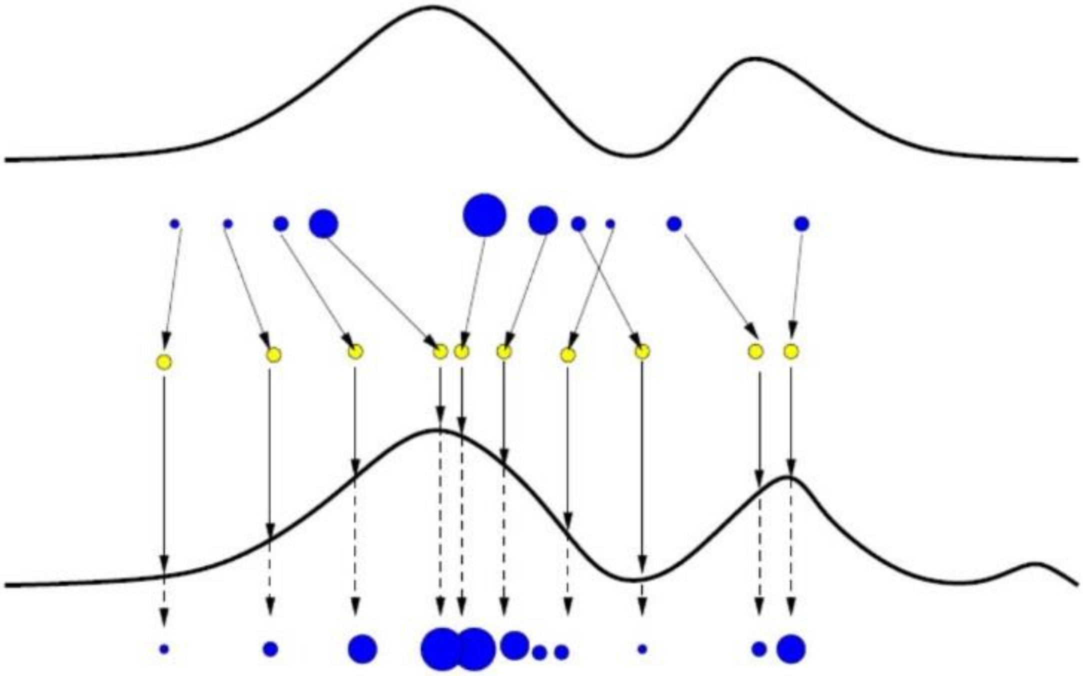

Fig. 6-1 Illustration of SIS [24] (from Ristic el at., 2004).

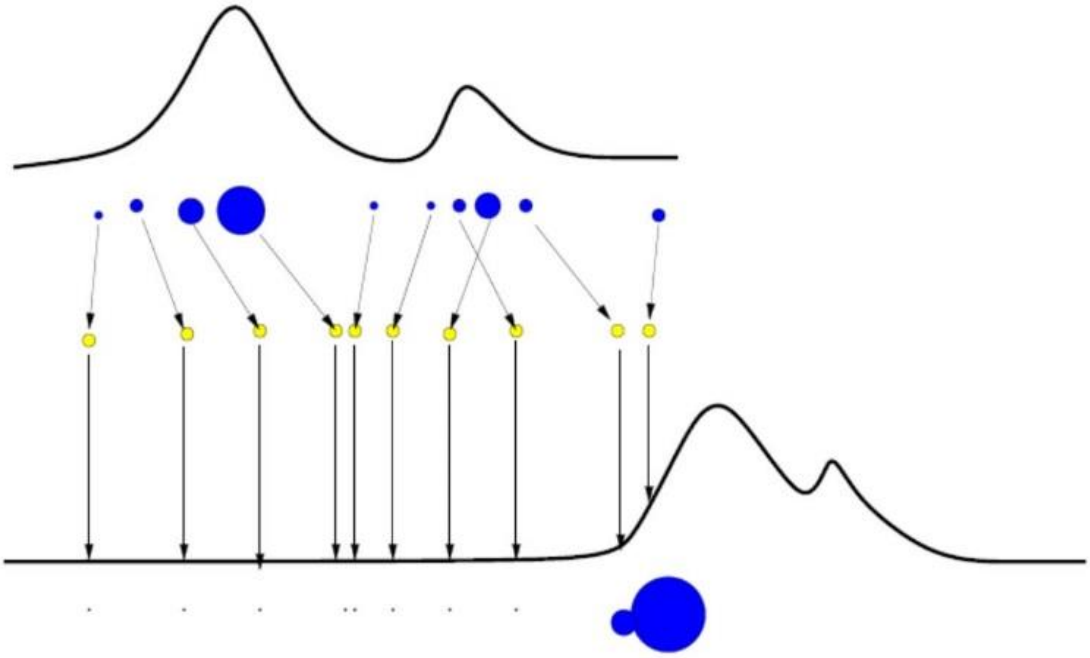

Fig. 6-2 Illustration of SIS - data conflict [24] (from Ristic el at., 2004).

The number of effective particles is used to measure the degree of particle weight degeneracy [25]:

$$N_{eff} = \frac{N}{1 + var\left(w_k^{*(i)}\right)}$$

$$w_k^{*(i)} = \frac{p\left(x_k^{(i)} \middle| y_{1:k}\right)}{q\left(x_k^{(i)} \middle| x_{k-1}^{(i)}, y_{1:k}\right)} \quad . \qquad (6-18)$$

Equation (6 – 18) means that as the number of effective particles decreases, the variance of the weight gets larger. The difference between the largest weight and the smallest weight thus increases, indicating that the weight degeneracy problem becomes worse. In practice, the number of effective particles can be approximated by:

$$\widehat{N}_{eff} \approx \frac{1}{\sum_{i=1}^{N}\left(w_k^{(i)}\right)^2} \quad .$$

When performing sequential importance sampling, if $\widehat{N}_{eff}$ is less than a preset threshold, the number of particles must be increased to overcome the weighted degeneracy phenomenon of the SIS algorithm, however, this will lead a corresponding increase in the complexity of calculation. Therefore, one of the following two approaches is used:

(1) Selecting an appropriate importance probability density function. One of the criteria for selecting the importance probability density function is to minimize the variance of the particle weights.

(2) Using a resampling method after sequential importance sampling that is called Sequential Importance Resampling (SIR).

6.2.5 Sequential Importance Resampling

The idea of resampling is to abandon the particles with small weight. To keep the same number of particles, new particles will replace the eliminated ones. The easy method to acquire new particles is to duplicate the ones that have higher values of weight.

The expectation problem has been converted into the form of a weighted sum:

$$p(x_k|y_{1:k}) = \sum_{i=1}^{N} w_k^{(i)} \delta\left(x_k - x_k^{(i)}\right) \quad . \qquad (6-19)$$

After resampling, the expectation is:

$$\tilde{p}(x_k|y_{1:k}) = \sum_{j=1}^{N} \frac{1}{N} \delta\left(x_k - x_k^{(j)}\right) = \sum_{i=1}^{N} \frac{n_i}{N} \delta\left(x_k - x_k^{(i)}\right) \qquad (6-20)$$

where $x_k^{(i)}$ is the particle at instant k, $x_k^{(j)}$ the resampling particle at instant k. The factor n_i refers to the number of times of particle $x_k^{(i)}$ is copied when a new set of particles $x_k^{(j)}$ is generated. The first equal sign in Equation (6 – 20) indicates that after resampling, all particles have the same weight, which is $1/N$, but some particles appear n_i times.

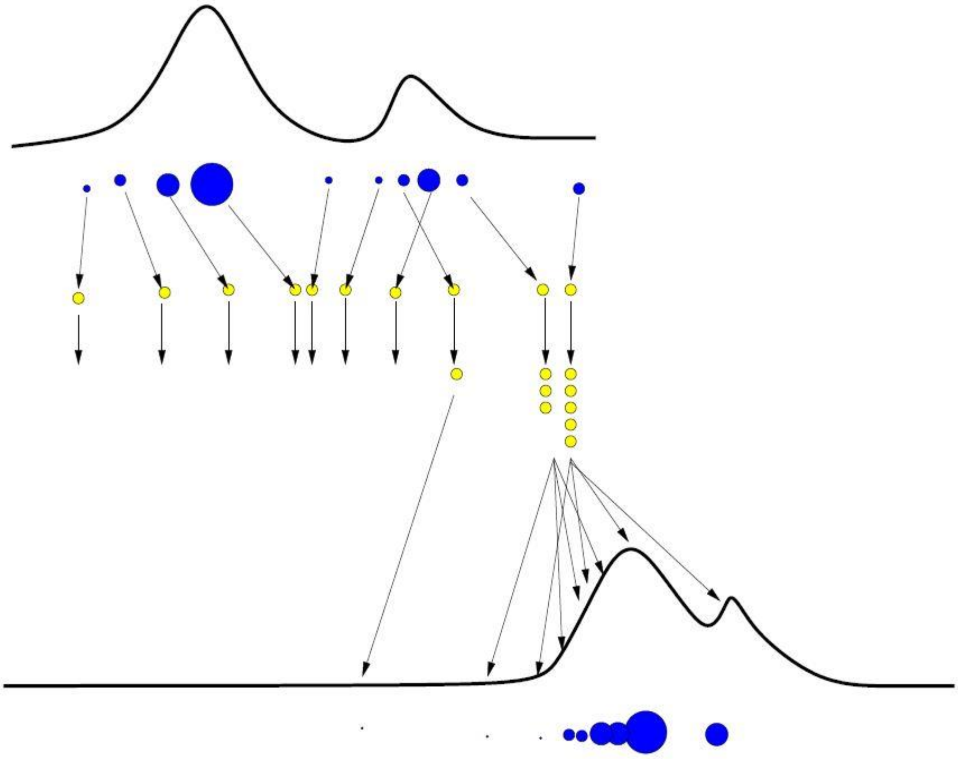

Fig. 6-3 SIR finding the higher weight particles [24] (from Ristic el at., 2004).

Fig. 6-3 and Fig. 6-4 diagrammatize the theoretical process of SIR. In order to reduce the number of particles with smaller weights, the improved resampling process filter out the particles with higher weights and move its concentration onto these particles. Fig. 6-3 shows the approach to find the higher weight particles, and Fig. 6-4 presents the algorithm focuses on the particles obtained from the previous step.

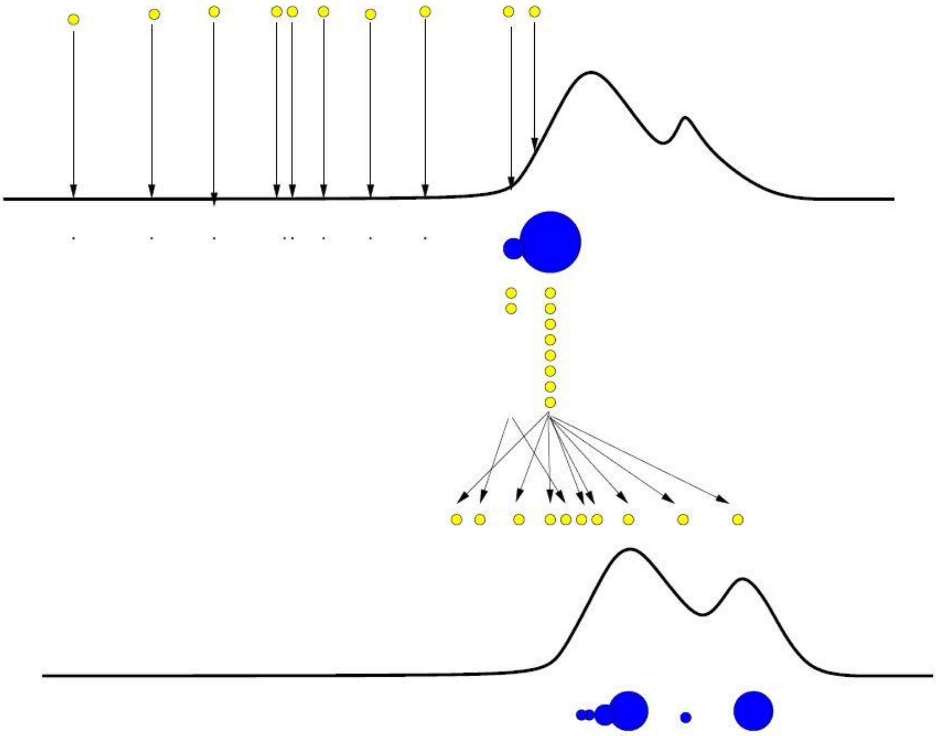

Fig. 6-4 SIR focusing on the particles from the previous step [24] (from Ristic el at., 2004).

Adapting the resampling method into the SIS algorithm that forms the basic PF algorithm.

The SIR filter is derived from the basic PF algorithm which needs to reform the particle importance probability density function. In SIR,

$$q\left(x_k^{(i)}\middle|x_{k-1}^{(i)}, y_k\right) = p\left(x_k^{(i)}\middle|x_{k-1}^{(i)}\right) \tag{6 - 21}$$

where $p(x_k|x_{k-1})$ is the prior probability. Substituting Equation (6 – 21) into Equation (6 – 15):

$$w_k^{(i)} \propto w_{k-1}^{(i)} p(y_k|x_k^{(i)}) \quad . \tag{6 – 22}$$

After each resampling process, there is $w_{k-1}^{(i)} = \frac{1}{N}$.

Then Equation (6 – 22) can be simplified to:

$$w_k^{(i)} \propto p(y_k|x_k^{(i)})$$

where the sampling probability $p(y_k|x_k^{(i)})$ indicates that the probability of *y* can be measured under the condition of state *x*.

According to the original system state equations (6 – 1), the measurement adds Gaussian noise near the true value, the distribution of y is a Gaussian distribution with the true measured value as the mean and a variance equal to the noise variance. Therefore, the sampling process of the weight when the particle is in the x state, produces a measurement y of the particle. The probability of this measurement y, if found by inserting it into a Gaussian distribution with the true value as the mean and the noise variance as the variance, i.e.,

$$w = \eta(2\pi\sum)^{-\frac{1}{2}} exp\{-\frac{1}{2}(y_{true} - y)\sum^{-1}(y_{true} - y)\} .$$

Thus, SIR is only related to the system state equation.

6.3 PaFiR Routing Protocol

In this section, the proposed DTN routing protocol is designed to tackle much more complicated scenarios than the one has been introduced in Chapter 4. The status update of mobile intelligent units and intermediate nodes occurs much more frequently. The input variations are nonlinear and non-Gaussian and the motion is categorized into the maneuvering model, which means the tracking and prediction circumstance cannot meet the definition of the basic LQG regulator.

As it has been reviewed in Section 6.2, the PF algorithm is very appropriate for tracking objects in complex scenarios that contain various states of moving objects. This is particularly true when UAVs are introduced into the system as intermediate relaying nodes to assist data packet forwarding. Here the proposed DTN routing strategy is termed as the Particle Filter Routing (PaFiR) protocol. Another strength of the PF algorithm is the number, *n*, of particles applied for processing can be adjusted to cut down the algorithm’s computational complexity. This is useful as the numerous smart terminals attached to the wireless DTN system differ greatly in their available processing resources such as, processing capacity, memory size and battery capacity and this is easily accommodated by adjusting the number of particles in the PaFiR routing algorithm.

6.3.1 Principles of Design

One of design purposes of the PaFiR routing protocol is to tackle on a hierarchical wireless relaying network that consists of the ground layer with one or multiple layers in the air. The applied scenario assumes that all intelligent devices deployed on the ground are completely free to move within the radio coverage area. The assisted UAVs cruise at a constant altitude dedicated for each aerial layer, and their cruising area can cover the ground network radio coverage or the lower aerial layer. All of network elements can be either maneuvering objects or non-maneuvering objects. In this thesis, the proposed routing strategy will address the single aerial layer network.

The air links between ground nodes or between UAVs and ground devices are taken to be bi-directional connections and the movement of ground portable devices and UAVs is observable when they are in the bi-directional radio connection range.

The PaFiR routing scheme can be a solution for offloading traffic from the conventional traffic bearing system voluntarily to balance the network data traffic load or for use as an emergency connection when the traditional mobile communication system is not available in the case of the incidents mentioned previously and with tolerable propagation delays.

6.3.2 Particle Filter Inferencing

As all of network elements in DTN system are autonomous, the movement states of portable devices and different types of UAVs could be extremely diversified, for example stable with zero speed and acceleration, steady speed with zero acceleration, small speed change with low acceleration (or deceleration) and significant speed change with high acceleration (or deceleration). Thus, in addition to maneuvering objects there are thus slow-moving or stationary objects classified as non-maneuvering. In the mathematical and statistical model, these different states are classified into two categories: a non-maneuvering model and a maneuvering model. The former assumes linear changes of state resulting in Gaussian distributions so that the filtering problems can be solved by Gaussian approximation [26], which is appropriate for the classical KF algorithm. The application of the KF algorithm for DTN routing strategy has been reviewed in Chapter 4 and Chapter 5. Here, the assumption can be made that when the state of moving objects is categorized as non-maneuvering model, they obey the precondition of the KF algorithm LQG regulator. Even if there are minor changes of states, these can be introduced as Gaussian noise and eliminated by the recursive KF procedure. The simulation results presented in Chapter 4 and Chapter 5 show the proposed KaFiR data relaying protocol performs well when tracked mobile targets are in less maneuvering states, but which gives a limitation of the routing protocol on the movement of network elements.

For wireless systems with complex multi-layer relaying networking in smart cities or other applications, there are many network elements that are required to have high mobility and this is particularly true for the scenarios will be introduced in the next chapter as UAVs are deployed into Network of Future (NoF) precisely because of their movement flexibility. When targeted objects start maneuvering, the filtering distribution becomes multi-modal and the state space presents as discrete making Gaussian approximations no longer applicable leading to a collapse of the LQG regulator precondition in KF. The mathematical model that has been discussed in Section 6.2 shows that the strength of the PF is that it applies the SMC method, is based on Monte Carlo methods using particle sets to express probabilities and can be used in any form of state space model to achieve online tracking.

To express the probability distribution, the algorithm extracts posterior probabilities through random state particles, which referred to as the SIS method. The PF algorithm refers to the process of obtaining a state minimum variance distribution by finding a set of random samples in the state space to approximate the probability density function instead of the integral operation with the sample mean. If more samples are given to describe the posterior probability distribution, the algorithm can approximate a more complex probability density function, and outcomes will be presented more accurately. However, the complexity of the algorithm will become higher in consequence hence costing more in terms of individual smart terminal processing capability and other resources to process it.

The design of the routing protocol for decentralized wireless networks has to consider various embedded resources on different portable device and minimize impacts on client applications and customer experience. It is necessary to estimate the appropriate value for the number of particles employed in the routing algorithm based on the various capabilities of the terminals deployed in the multi-layer wireless relaying network applications and the scenario in which devices are required to work. As an option, the design of the routing protocol may introduce this estimation process as an adaptive function, after the air connected nodes exchange information, the protocol self-adjusts the number of particles to balance the algorithm complexity and prediction accuracy.

6.4 Summary

This chapter provides a detailed mathematical review on the theoretical basis of each step applied in the PF algorithm that are of interest to the proposed relaying strategy. As a rigorous state space estimation approach, the PF algorithm consists of several different well-developed technologies to ensure the success of the algorithm, in particular for applying particles to probability densities to overcome the complicated integral operation of Bayesian posterior probabilities. This makes the algorithm cope with the complex tracking and prediction tasks, for instance, the maneuvering model or hybrid model. The flexibility of the algorithm and recent improvements in smart portable devices make possible the application of the PF.

In order to better fulfil the PF algorithm within the routing protocol designed for decentralized wireless networks and adapt it into complex scenarios properly, the design principle has been defined, and the inferencing process has been tailored to more applicable for the DTN relaying strategy.

By taking the advantages of the PF algorithm, the PaFiR DTN routing protocol is designed to be deployed in some applications with complex system structures and diversified movement characteristics of wireless network elements. The simulation and test outcomes of the PaFiR relaying strategy and comparison with other existing DTN routing plans will be presented in the next chapter.

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Chapter 7

PaFiR for UAV aided mobile IoT Smart City systems and Beyond

7.1 Related Works

The development of the big data era has resulted in information systems and intelligent knowledge processing playing an increasingly essential role in everyday life [1]. Moreover, machine learning with big data revolution is changing the ways of living, working, studying and thinking [2]. Smart digital devices are increasingly everywhere to keep collecting various pieces of information, but these are commonly in the form of only the raw and rough digital symbols, digits, graphs or images. The information cannot mean anything without any process, such as machine learning [3] [4], data mining [5], pattern recognition [6], data analysis [7] and knowledge discovery [8]. All these applications give rise to significant demands on data transmission and processing that cause exponentially increasing requirements for data communication networks and affiliated technologies. The idea of the network of the future (NoF) is a technology fusion of the future network design that includes the multi-layer network structure and hybrid system. Flying network platforms are an essential part of the different communication systems [9].

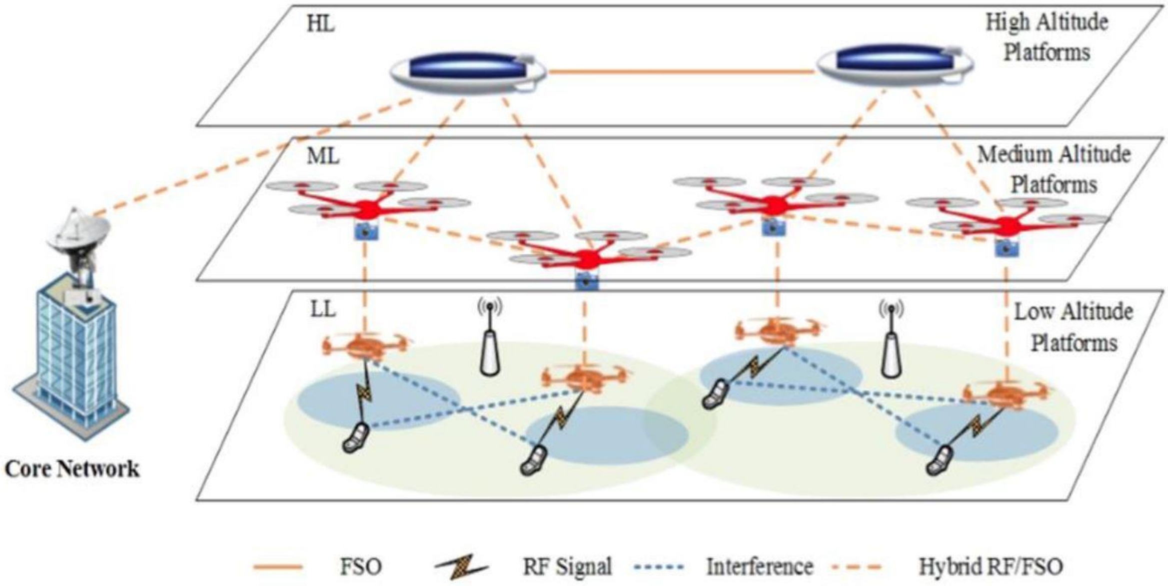


Fig. 7-1 Multi-layer UAV assisted network flying platform [10] (from Shakir, 2017).

The application of UAV technology allows mobile networks to easily acquire the characteristics of flexibility, energy-efficiency and adaptability for multiple applications. The UAV aided mobile IoT system could be a part of the multi-layer network flying platform in the NoF, since both wireless systems can share flying intermediate nodes to relay the data packets. Fig. 7-1 [10] shows a UAVs assisted network flying platform with a Multi-layer structure that forms a substantial complex system for movement analysis.

7.2 Relay Hop Selection

In this PhD work, the case study introduced here is Vertical FSO-based Front haul for Ultra-dense HetNets that a NoF mobile system with single-layer network flying platform as shown in Fig. 7-2 [12]. In accordance with the assumptions stated in Section 6.3.1, the UAVs fly horizontally at a constant altitude and the movement of each for the flying platform can be projected to a two-dimensional trajectory on the ground. In the mathematical and statistical model, the motion of the UAV can be mapped onto the ground and processed as a ground moving node. Given the freedom of movement of each element involved in the NoF system, the movement of each node is a random motion meaning that UAVs and ground mobile devices establish a stochastic system, which can be represented by a stochastic process. This random motion (or movement state) is measurable for other mobile users as long as they are in bi-directional radio connection range. The state of surrounding nodes is collected by the observers in every instant, and the collected data (locations, velocities and accelerations or decelerations) are the samples to be used to track and predict the motion of targeted objects in a future moment.

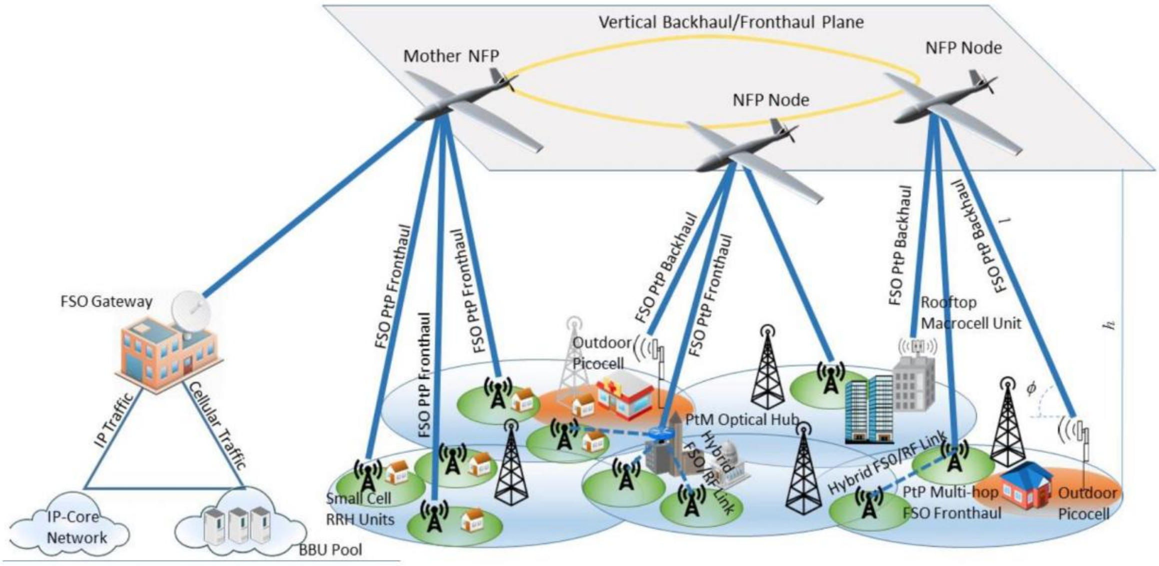


Fig. 7-2 Vertical FSO-based Fronthaul for Ultra-dense HetNets [12] (from Alzenad et al., 2018).

However, the real states of the observed targets could be different from the observations in a certain instant so two different data categories are defined: (a) the unknown real state of the observed portable device which is denoted by X; (b) the observed data of a targeted node which is denoted by Y. Based on the mathematical and statistical model, the unknown data comprising X can be computed using the observed data Y by reasoning or tracking that includes a series of filtering, prediction and smoothing operations relying on the Bayesian statistical approach [11].

Within the SCF relaying mechanism, source nodes or intermediate nodes need to find an appropriate relaying node for forwarding the data packets towards their destinations. When a message is generated by a source device or stored and carried by an intermediate node, an observation takes place to gather the movement state of neighbouring network elements with the ability to create a bi-directional radio connection to relay the message. The observed data give the input as the prior probability distribution for the PF algorithm to predict the movement state of portable nodes in the next moment, which implies the transmission probability of the observed device moving towards the destination to deliver the message. After the packet holding smart device replicates the observation and prediction procedure for each surrounding bi-directional connected mobile node, it will have a comprehensive list of transmission probabilities for all adjacent portable terminals. After the transmission probabilities are exchanged among the serving nodes, each message holding intelligent device will have knowledge of the transmission probabilities of every potential hop along the forwarding path toward the message destination. The node with the highest transmission probability will then be selected to relay the packets. If the next hop is not present, the intermediate node will store and carry the packets until the appropriate node appears.

When only low transmission probability nodes are available for relaying packets, to avoid inappropriate relaying actions taking place, an optional predefined threshold t may be utilized. Thus, if the transmission probabilities of all surrounding smart devices are lower than t, the relaying process will be paused and the message will be buffered by the carrying node. The transmission threshold is designed to help the NoF mobile system planner design a parallel DTN system to balance the traffic load or make a backup solution in emergency cases, to satisfy different system performance criteria in various scenarios regarding delivery probability, average latency, message hop count and energy consumption. For some instances, a higher value of transmission threshold ensures that the message is relayed to a more reliable forwarding device. This does, however, cause the message to suffer a longer delay waiting for an appropriate relaying node, potentially increasing the overall average latency. The strength and purpose for the transmission threshold is to save the message hop count and transmission energy consumption. As high transmission probability intermediate nodes rarely appear in some scenarios, the predefined transmission threshold cannot be very high, and the application circumstance has to be considered carefully.

7.3 Forwarding Strategies

Given the advantages and disadvantages of forwarding strategies for different DTN routing protocols that have been compared in Section 3.4.2, the proposed PaFiR DTN routing protocol uses the current status of network nodes to forecast the future pattern of the network topology. This is especially pertinent to the movement trajectory pattern of UAVs with high mobility, even using energy efficient routing they present a very different behaviour to ground-based portable nodes [13]. Conventional forwarding strategies are not applicable to cope with the complex scenarios exhibiting highly diversified behaviour appearances but the nature of the PF algorithm makes it easy to track and predict different mobile patterns of ground smart terminals and UAVs.

7.4 Routing Protocol Simulation

7.4.1 Introduction

The current version of the ONE simulator does not support three-dimensional trace data, and there are no three-dimensional object movement trace data available for the public use. All proposed applications and scenarios were thus mapped into a two-dimensional model, and the mapping approach of the single-layer network flying platform has been introduced in Section 7.2. If the multi-layer network flying platform in NoF had more than one aerial layer, the UAV flying trace of upper layer was mapped to the lower layer, and then aerial layers were projected onto a two-dimensional trajectory on the ground.

The entire simulation process will be presented in two parts. The first part was designed evaluate the individual performance of the PaFiR message forwarding protocol produced, and test it with various parameters to simulate different application scenarios. The second, compared the PaFiR relaying strategy will with some existing routing plans to find the best solution for the multi-layer network flying platform in NoF.

7.4.2 Performance Evaluation

The testing and simulation process followed here was that introduced in Chapter 3. In this section, the process will be followed to evaluate the performance of resilience and tolerance of proposed PaFiR DTN protocol. The sample dataset was generated by the ONE simulator event generator utilized to simulate a complex wireless network condition has been described in Chapter 4. As has been introduced in Section 3.5.2, the map data was the downtown area of Helsinki city including road and pedestrian walk paths. The connectivity traces for the real time location data of various moving objects in the defined region carrying portable smart devices, such as pedestrians, cars and trams, were generated by the ONE simulator. Parameters for the simulation configurations were as specified in Table 7-1. These were chosen to be of the same order as the parameters in [14] with the buffer size large enough that it did not impact performance.

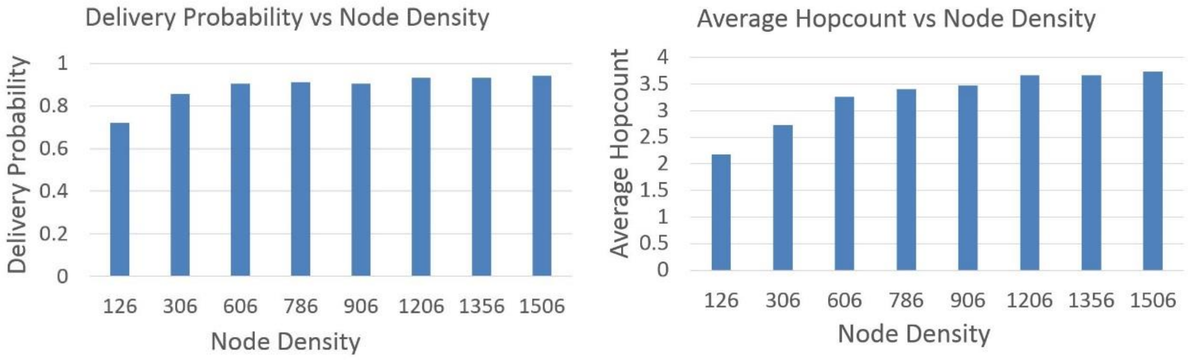
TABLE 7-1 PARAMETERS OF SIMULATION CONFIGURATIONS

Parameters	**Value of parameters**
Simulation Time (second)	86400
Buffer Size (MB)	10, 20, 50, 75, 100, 200, 500
Packet Lifetime (TTL) (minutes)	60, 120, 180, 240, 300, 360, 420
Message Interval (second)	3, 5, 10, 20, 30, 60
Message Size (MB)	0.3-0.5, 0.5-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-7
Number of Nodes	126, 306, 606, 786, 906, 1206, 1356, 1506

The message interval simulated the information rate of the sender. The parameters for this category tested the circumstances from a low packet generation rate of 1 packet per minute (67 kbps) to a high packet generation rate of 20 packets per minute (1.33 Mbps). The number of nodes varied the density of the wireless system from a low-density (126 nodes) mobile network to an extremely high-density (1506 nodes) system.

In this part of work, there are four key factors of wireless system that are addressed to evaluate the overall performance of proposed mobile routing strategy, which are: Delivery Probability, Overhead Ratio, Average Latency and Average number of hops. The variety of simulation parameter against different performance metrics are given as follows:

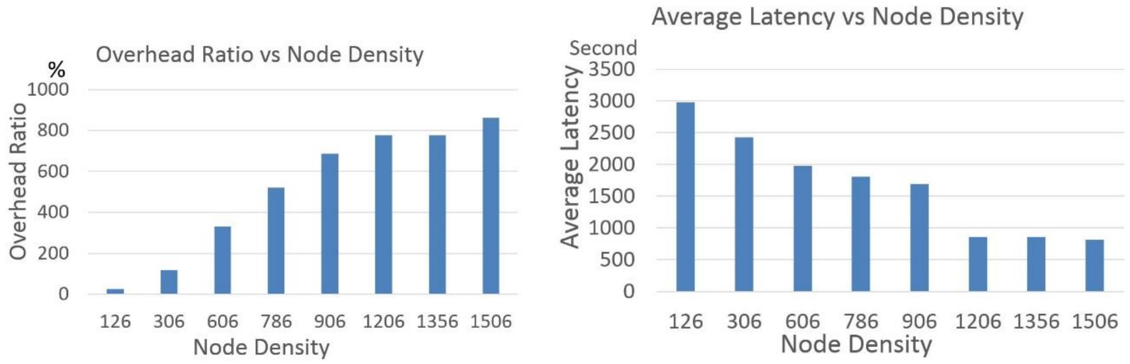
7.4.2.1 Node Density



(a) (b)

Fig. 7-3 (a) Delivery probability; (b) average hop count for different network densities.

Fig. 7-3 shows that the delivery probability and average hop count reach an approximately steady state when the total node number exceeds 606. The delivery ratio remains above 0.9 with a highest point of 0.941 when the node population is 1506. This means that the PaFiR protocol can handle the high density network and keep improving its performance with the increase in the number of nodes. At the same time, the average hop count only slightly increases from 3.3 to 3.7, even if the node population almost triples.

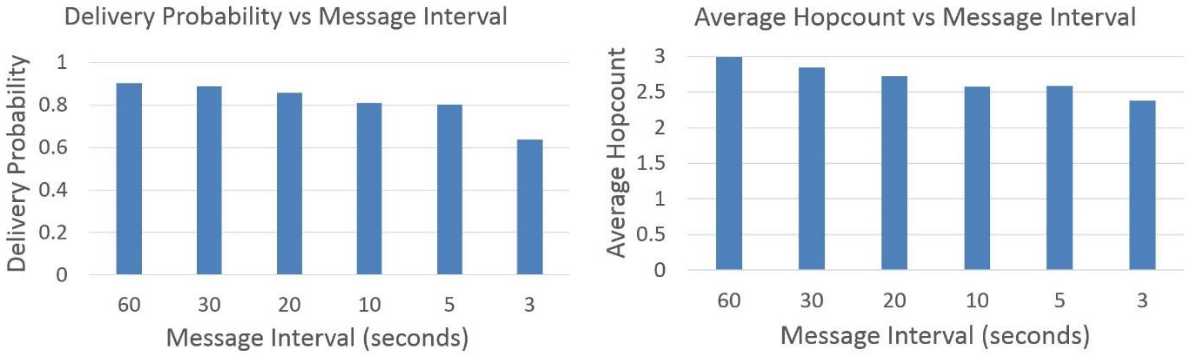


(a) (b)

Fig. 7-4 (a) overhead ratio; (b) average latency for different network densities.

Fig. 7-4 indicates that the changes of overhead ratio and average latency are almost in the same step. The increase of the overhead ratio slows down when the node density is over 1000. Meanwhile, the average delay time drops from 2974 seconds to 819 because more candidate nodes participate into the message relaying process and PaFiR can manage to find the better or best intermediate nodes to forward data packets.

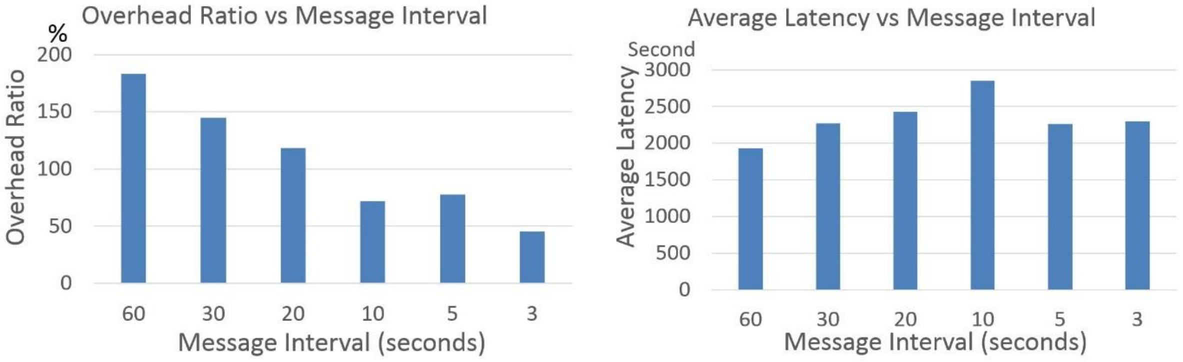
7.4.2.2 Message Interval



(a) (b)

Fig. 7-5 (a) Delivery probability; (b) average hop count for different message generation intervals.

Fig. 7-5 presents that the delivery probability has a decrease when the message generation rate increases, however, the delivery ratio only has 10% drop from 0.91 to 0.81 when the generation interval changes from 60 seconds per message to 5 seconds per message. The large decrease happens when the message interval changes from 5 seconds to 3 seconds, but for DTN system such high message generation rate is rather rare. The constant decreasing of average hop count improves the system performance since smaller hop counts consume less transmission energy to relay the data packets.



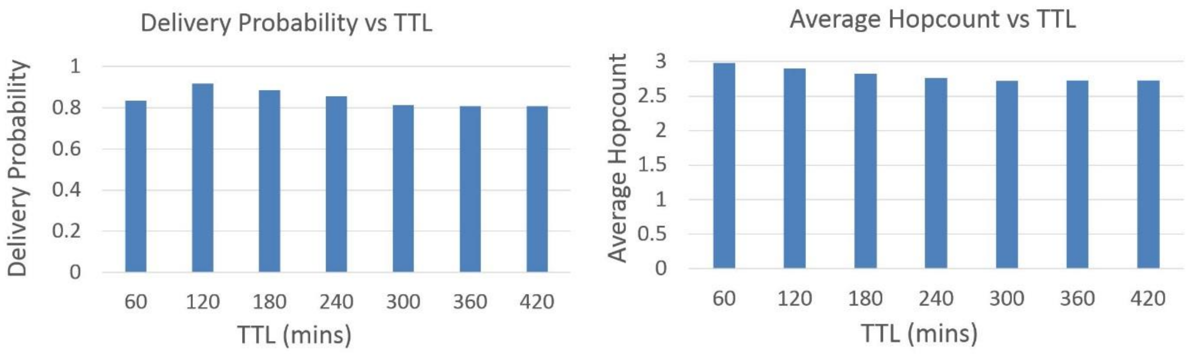
(a) (b)

Fig. 7-6 (a) overhead ratio; (b) average latency for different message generation intervals.

Fig. 7-6 reveals that the overhead ratio becomes only a quarter as the data rate increases from 67 kbps to 1333 kbps. The average latency has a drop after increasing from 1929 seconds to 2851 seconds and stays at 2263 seconds and 2299 seconds when the message interval is 5 seconds and 3 seconds respectively.

The PaFiR routing scheme exhibits a good overall performance, in particular with respect to tackling the heavy data traffic between nodes, PaFiR does not show a substantially degraded overall result.

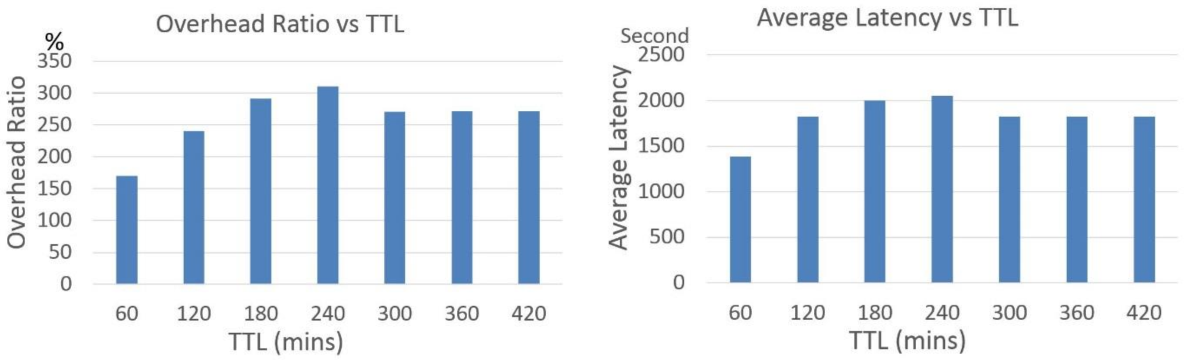
7.4.2.3 Time To Live



(a) (b)

Fig. 7-7 (a) Delivery probability; (b) average hop count for different TTL in mins.

In Fig. 7-7, the diagrams indicate that the delivery probability only fluctuates between 0.81 and 0.92, and it gets steady after message lifetime is larger than 240 mins. The average hop count drops from 2.98 to 2.76 as the TTL increases from 60 mins to 240 mins, then slows down and remains the same from 360 mins to 420 mins.

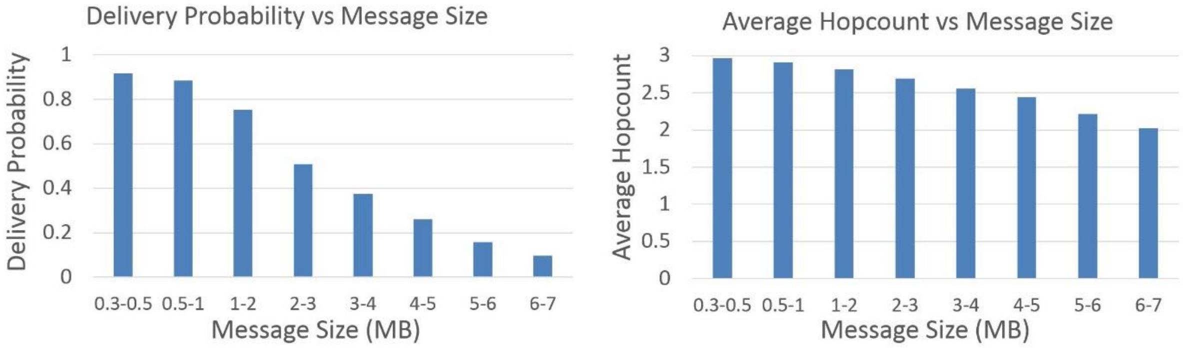


(a) (b)

Fig. 7-8 (a) overhead ratio; (b) average latency for different TTL in mins.

The changes of the overhead ratio and average latency display the same pattern in Fig. 7-8. A substantial increase happens as message lifetime rises from 60 mins to 240 mins, then there is a 20% drop and to a level that remains unchanged for the rest of the parameter changes.

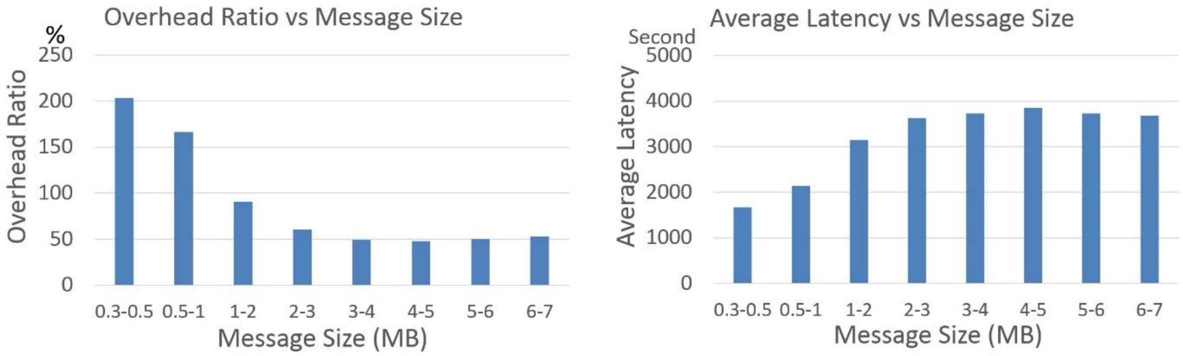
7.4.2.4 Message Size



(a) (b)

Fig. 7-9 (a) Delivery probability; (b) average hop count for different message size.

Fig. 7-9 shows that increasing the message size affects the delivery probability significantly. The delivery probability is acceptable for the majority of DTN services while the data packet size extends from 0.3-0.5 MB to 1-2 MB; the delivery ratio decreases from 0.92 to 0.75, however, when the size exceeds 2MB, there is a rapid reduction. The ratio is only 0.097 by 6-7 MB that makes most of the nodes unreachable as most of messages are dropped during the relaying process. The average hop count only has one hop reduced when packets become 20 times larger so is less affected.



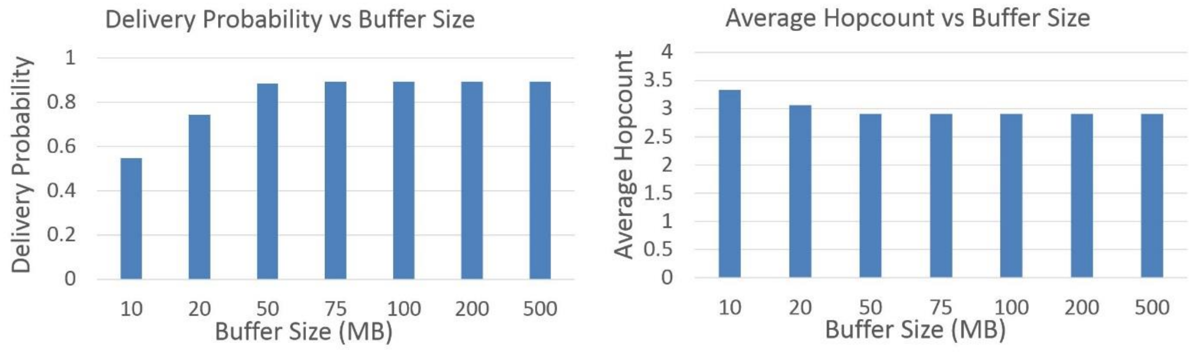
(a) (b)

Fig. 7-10 (a) overhead ratio; (b) average latency for different message size.

By a ten times expansion of message size from 0.3-0.5 MB to 3-4 MB, the overhead ratio has more than four times improvement from 203% to 50%, meanwhile, the average time delay grows from 1673 seconds to 3733 seconds.

These test results imply that the PaFiR routing protocol is more appropriate for services that generate small messages or applications that encapsulate data in to small packets, and it is better to keep the size is smaller than 1MB.

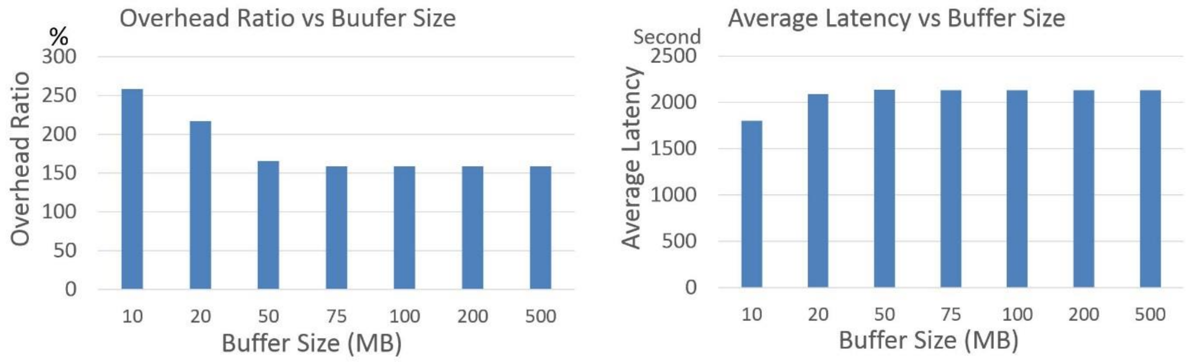
7.4.2.5 Buffer Size



(a) (b)

Fig. 7-11 (a) Delivery probability; (b) average hop count for different buffer size.

Fig. 7-11 presents that when the capacity of the buffer on smart terminals reaches 50 MB, the expansion of buffer size will not help to improve the system performance. For the delivery probability, it rises from 0.55 to 0.88 and then remains at 0.89 when the buffer size is bigger than 50 MB. The average hop count reduces slightly from 3.33 to 2.91 and stays at the same value when more cache is given.



(a) (b)

Fig. 7-12 (a) overhead ratio; (b) average latency for different buffer size.

As it can be seen in Fig. 7-12, the overhead ratio drops by almost a half when the buffer extends its size from 10 MB to 75 MB. At the same time, only 18% of extra time delay is added to the entire packet forwarding process.

7.4.3 Performance Comparison with Other DTN Routing Protocols

In the last section, the overall performance of the proposed PaFiR DTN routing protocol has been tested comprehensively, and the results have indicated that PaFiR can deliver a good overall result in complex wireless network conditions. In this section, the simulation process will be used to verify under the same mobile system conditions whether PaFiR can present an outstanding achievement among some existing classical DTN routing strategies and the KaFiR packet forwarding algorithm has been introduced in Chapter 4 and 5, in particular when the population of portable smart devices expands from a sparse network to high dense system.

Parameters for the simulation configurations in this part are specified in Table 7-2.

TABLE 7-2 PARAMETERS OF SIMULATION CONFIGURATIONS

Parameters	**Value of parameters**
Buffer Size (MB)	15
Message Time To Live (TTL) (minute)	60
Message Interval (second)	25-35
Message Size (MB)	0.5-1
Number of Nodes	126, 156, 186, 306, 606, 906, 1056
Simulation Time (second)	18000

The simulation outcomes reveal that the PaFiR routing protocol delivers an excellent performance compared with the existing DTN forwarding methods. In Fig. 7-13, the delivery probability of the PaFiR protocol exhibits a constant improvement as the density of the wireless network increases, which means that as more mobile subscribers join the network it becomes more reliable. For instance, when more than 1000 IoT devices are involved in the network, the delivery probability can reach 0.9 which is 40% increased when the population grows by almost one order of magnitude. The Epidemic protocol performs well in lower density DTN networks but when the number of smart nodes exceeds 186, the delivery rate decays fast. PRoPHET shows good performance only when the portable device population is less than 606. After the sum of smart terminals in the system exceeds 909, the delivery probability starts dropping much more quickly. The delivery rate of Spray and Wait only fluctuates between 0.55 and 0.69 and most of parts are the worst among the tested protocols, and the trend shows that it will have a further decrease when the number of portable nodes is over 1000. The KaFiR protocol is the only one that maintains the same growth trend as the PaFiR protocol but it is always approximately 0.05 worse.

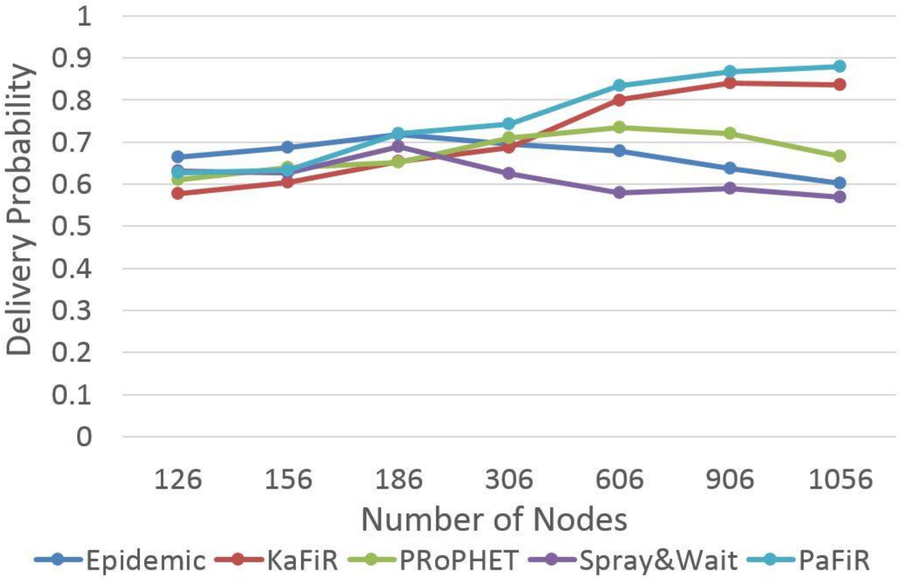


Fig. 7-13 Delivery Probability vs. Number of Nodes.

In Fig. 7-14, the average latency of the different forwarding schemes, except Spray and Wait, follows the same downward trend as the number of smart nodes increases but PaFiR has the strongest performance as the overall time delay drops much faster than any of the other schemes. When system population is greater than 550, PaFiR presents the least time of delay. As the node number grows from 126 to 1056, the average latency is reduced by 40%. Spray and Wait performs well only when the device population is small and does not benefit from the growth in the number of nodes.

In Fig. 7-15, Spray and Wait keeps the overhead ratio at a very low level all the time, meanwhile, KaFiR and PaFiR stay in the same trend, and PaFiR is about 5% higher than the KaFiR when the node population is greater than 306. Epidemic and PRoPHET begin to increase rapidly after number of nodes exceeds 306.

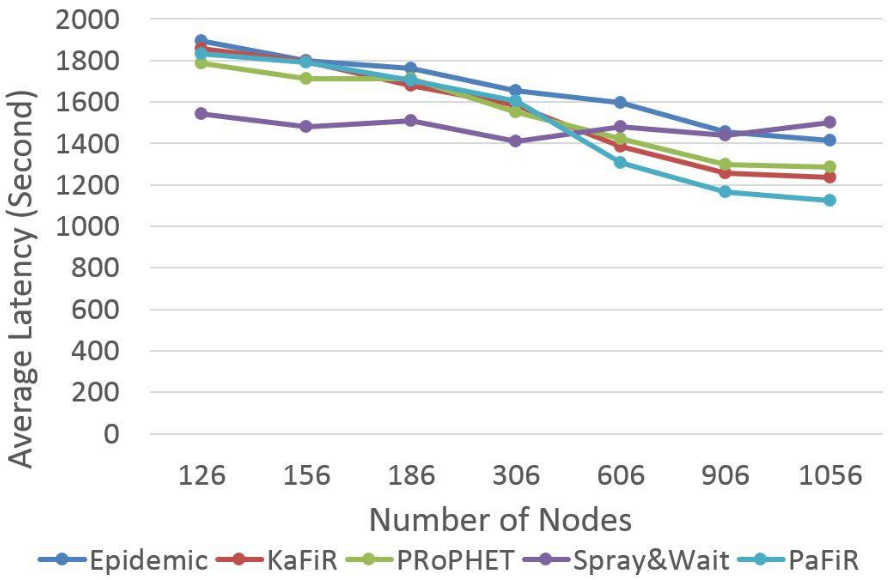


Fig. 7-14 Average Latency vs. Number of Nodes.

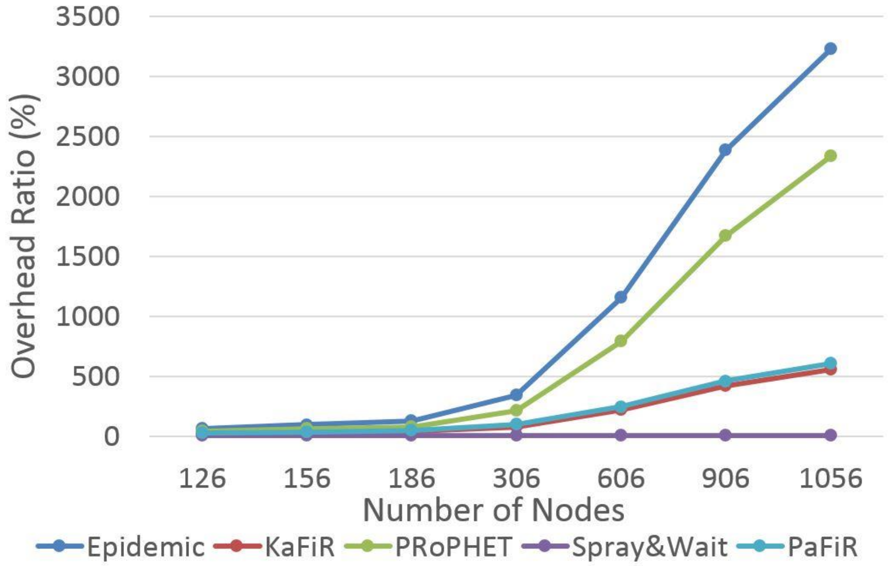


Fig. 7-15 Overhead Ratio vs. Number of Nodes.

In Fig. 7-16, SprayAndWait has a very stable average number of hop count, in contrast, Epidemic and PRoPHET have a significant growth after the nodes population is more than 306. KaFiR and PaFiR have almost the same average hop count all the time, and only one hop is added when the node population grows almost ten times. This means that even in a dense network, the PaFiR protocol can manage the number of relaying events as well as in a sparse system without many more intermediate nodes being required.

All the results show that the PF prediction algorithm assists the protocol in tracking and inferring the movement of ground intelligent gadgets and associated UAVs. Hence, the proposed PaFiR routing protocol offers an extremely competitive performance with respect to all key assessment metrics when the mobile network becomes more complex.

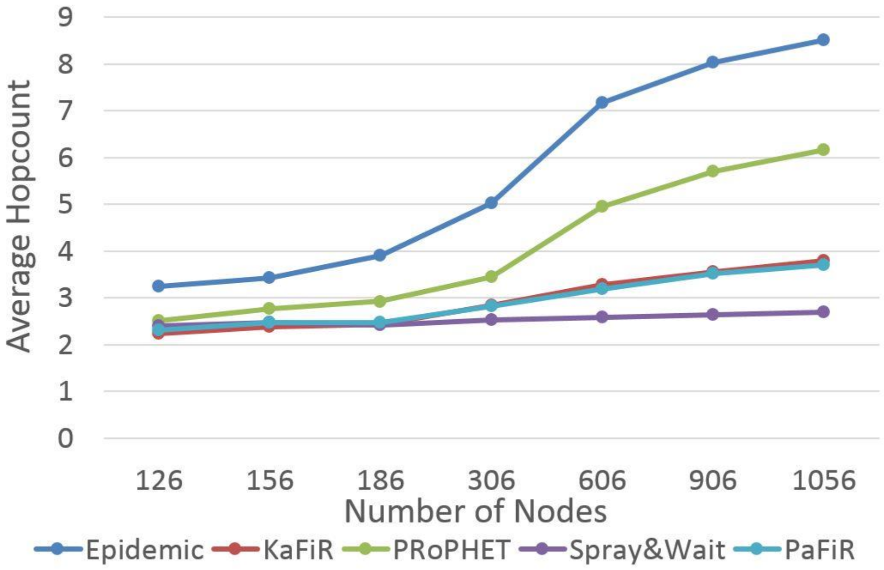


Fig. 7-16 Average Hopcount vs. Number of Nodes.

7.5 Summary

In Section 7.4.2, the test and simulation results show that the proposed PaFiR routing protocol delivers a better overall performance when the population of portable intelligent devices in the network is large, which means PaFiR is very appropriate for complex network scenarios that consist of a large number of moving smart terminals. This characteristic can meet the design requirements of applications deployed in the network flying platform in NoF.

In Section 7.4.3, the comparison results indicate that the PaFiR relaying strategy displays a substantial outstanding performance on scalability, resilience and tolerance among the candidate existing DTN routing protocols, in particular for the condition of high node density with moderate date traffic load. These results extend the outcomes from Sections 7.4.2 to demonstrate that in complex DTN wireless networks the PaFiR routing protocol can replace existing DTN solutions in most application scenarios.

With the flexibility of portable smart devices and assisted UAVs deployed in single-layer or multi-layer network flying platform in NoF, and the variety of application and service demands, a DTN routing protocol needs to cope with extremely complex scenarios. The characteristics of the PF algorithm endow the PaFiR routing protocol with more tolerance, resilience and scalability than other current relaying schemes. The movement prediction capability of the PaFiR routing protocol potentially enables the mobile system with UAVs assisted flying platform to provide more functionalities and applications, such as positioning services, behaviour analysis and object tracking.

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Chapter 8

Conclusions and Future Work

As a result of the rapid development and deployment of IoT, Smart Cities and other new ICT technologies and applications, there are exponentially increasing demands for data communications. Current options for system expansion cannot meet these substantial data traffic requirements. Moreover, the vulnerability of communication systems adds to the pressures on modern communications infrastructure. Thus, as a system backup and traffic flow diversion plan, decentralized wireless network solutions have been the focus of research attention and have become a significant emerging communication paradigm in recent years.

In this thesis, the issues and challenges of decentralized wireless networks were first reviewed, then the state of the art of potential technologies and applications for the problems were addressed. Arising from this consideration, two proposed DTN message relaying solutions were under scrutiny, which applied Bayesian filtering approaches into decentralized wireless network routing strategies to determine the selection of intermediate relaying nodes to optimize the overall performance of mobile DTN system. The testing and simulation results show that relaying protocols designed present very promising performance with respect to resilience, tolerance and scalability.

8.1 Conclusions and Contributions

8.1.1 KaFiR DTN Routing Protocol

The proposed KaFiR DTN relaying scheme makes use of the KF algorithm that is an *optimal recursive data processing algorithm* [1] and provides the online estimation solution to solve the object tracking problem. A detailed evaluation of the performance of the protocol that utilizes the KF algorithm models has been presented, which has shown that such an approach enables smart gadgets to track and predict the motion of a nearby targeted mobile node and assist it to determine the next message relay as a better or best option for a relaying route to its destination. Meanwhile, the KF algorithm itself is rather small and simple and thus a wide range of smart terminals are able to process the program. Moreover, the KaFiR protocol does not require substantial memory resources to store the movement history of tracked intelligent mobile nodes.

The subsequent routing protocol simulation results proved the theoretical idea. In simple networks, the designed KaFiR routing protocol takes maximum advantage of Direct Delivery routing to maintain its overhead ratio at zero and the number of hops as one. This means that the KaFiR protocol offers efficiency without wasting any resource to transfer unnecessary packets. Meanwhile, employing fewer hops saves packet forwarding energy and avoids surplus intervention by intermediaries, since portable devices have limited power and buffering space; this minimizes the negative effects on other mobile subscribers and the whole wireless system.

For complex networks, the KaFiR routing scheme benefits from the growing number of host nodes as there are more candidates in the prediction pool for the relay selection, so the delivery probability can steadily rise without affecting other evaluation key factors. The relevant simulation work showed that in sparse networks, the KaFiR relaying strategy exhibits similar delivery probabilities, latency and hops counts to established protocols such as Spray and Wait. Although some of the advantage is lost with dense and complex networks, the simplicity of the proposed protocol offers utility to, for example, small sensor networks. Its modest bandwidth requirements also offer advantages in constrained communication environments.

Nevertheless, the results indicate that at modest node densities, the protocol will deliver between 60% and 80% of the messages but after a substantial delay. Thus, real-time applications will not be well served by the simple approach taken here but it will be useful, for example in data collection as part of the services and applications for mobile IoT in smart cities.

8.1.2 PaFiR DTN Routing Protocol

The PaFiR DTN routing protocol designed utilizes the strength of PF algorithms by endowing mobile nodes with the intelligent ability to acquire and predict movement knowledge of surrounding nodes. This is achieved by running the PF algorithm on smart devices and thus assisting them to find the next hop as a better or best option for a message relaying route. PaFiR allows the smart terminals to tackle some more complicated scenarios with mixtures of non-maneuvering and maneuvering subscribers in some complex applications and services with a hierarchical network structure.

The PaFiR DTN routing protocol shows itself to be a versatile and useful one that contributes wide ranging excellent scalability, resilience and tolerance when compared via comprehensive simulation outcomes to the other existing DTN relaying schemes tested. Therefore, it is a general purpose paradigm that offers steady outcomes in a broad range of system conditions that lift the KF LQG regulator precondition, to ease the uncertainty without significant changes to key network factors. This is a significant advantage since it is desirable in mobile DTN networks for protocols to deliver near equal overall performance under unpredictable conditions, which fully satisfy the needs of wireless system innovation from flat network structures to multi-layer systems. The PaFiR DTN routing protocol offers the wireless system planner good opportunities to design a more synthetical and massive deployed UAV assisted decentralized wireless networks with multiple aerial layers for NoF applications.

8.2 Research Extensions

8.2.1 KaFiR DTN Routing Protocol

The simulation and test results indicate that the KaFiR routing algorithm will face challenges when significant numbers of wireless users fall into the category where a maneuvering model is needed. When the user is moving unsteadily, both the direction and the velocity could be changing at all times; in that case, acceleration or deceleration will be included in future as another dimension of the state vector to indicate the state of the mobile subscriber. However, as the dimension of the inputs becomes high, the calculation volume will substantially increase exponentially. Thus, to let the relaying protocol still be available for individual smart devices, the computation complexity and computation time for different intelligent terminals should be taken into account.

The KF is a classical optimal prediction and tracking algorithm, the KaFiR routing protocol is suitable for many scenarios, since only a small portion of wireless users will exhibit high mobility [2]. Nevertheless, to further broaden the application and concept of intelligent relaying schemes for UAV aided mobile IoT systems other algorithms can be considered that can improve the prediction and tracking performance for a maneuvering or more complicated scenario. Prime candidates for the research extension of current work are the Extended KF (EKF) [3], Unscented KF (UKF) [4], the Interactive Multiple Model (IMM) algorithm [5] and other potential filtering schemes [6], along with more applications and services in mobile DTNs.

8.2.2 PaFiR DTN Routing Protocol

The simulation results show that the PaFiR routing protocol delivers excellent performance when compared with other relaying strategies; the PF algorithm is rather rigorous and its computational complexity is affordable for portable smart terminals deployed in the system. In a further research extension, the movement prediction can cooperate with UAV trajectory optimization [7] [8] to improve the accuracy of prediction and to optimize the packet relaying path and reduce the energy consumption. Also, by consideration of the optimization of data packet relaying paths, balancing of the data traffic flow [9] to increase the overall complex multi-layer mobile system performance can be achieved.

To extend the current research, the best candidates could be Finite set statistics (FISST) [10] [11], and some latest advanced rigorous filtering algorithms, such as random point based filters [12], auxiliary particle filters [13], box-particle PHD filters [14], Gaussian mixture particle filters [15] and Rao-blackwellised particle filters [16].

8.2.3 Machine Learning

In this thesis, the movement tracking and prediction of moving objects are proposed by the Gaussian filtering approaches, however, such reasoning tasks also can be achieved by machine learning [17] [18]. This is one of the emerging fields of computer science, which is also based on mathematical and statistical theories to endow computer systems with intelligent abilities to undertake *learning* tasks. The terminology for machine learning was coined by Samuel in 1959 [19], and it also can refer to the artificial intelligence (AI) [20] [21].

As the observing mobile subscriber measures the target mobile node by sampling the location, velocity and acceleration or deceleration information in the discrete time, discrete-state Markov models within machine learning may be used [22].

The neural network [23] is one of the important research branches of AI, which abstracts the human brain neuron network from the perspective of information processing, establishes a simple model, and forms different networks according to different connection methods. In 1943, McCulloch and Pitts established the preliminary concept of artificial neural networks (ANNs) and the mathematical model of artificial neurons is proposed and presented in [24], thus creating an era of ANN research. Neural networks were further developed by American neuroscientist Rosenblatt who proposed that a machine that simulates human perception and is called ‘perceptron’ in 1957 [25]. The perceptron is a simple form of feedforward neural network, which is a binary linear classifier. It can be used to program a simple routing algorithm to identify the better or best intermediate relaying node to the destination. For complex scenarios, ANNs some more sophisticated techniques, such as recurrent neural networks (RNNs) [26], deep learning [27] and other technologies [28].

The Support Vector Machine (SVM) [29] is a terminology first coined by Cortes and Vapnik in their 1995 research paper [30]. The SVM has many advantages in solving small sample, nonlinear and high dimensional issues, and can be applied to other machine learning problems such as function fitting, so it can be applied to solve the problem for complex applications and services in a large scale DTN system [31].

Bayesian decision theory [32] is another branch in machine learning to solve the problem of pattern recognition [33], which uses Bayes' rule [34] to estimate the unknown state bases on the incomplete information. Then, the Bayesian formula is used to correct the probability of occurrence, and finally the expected value and the modified probability are used to make the optimal decision.

8.3 Future Work

The decentralized wireless network can be the solution when conventional mobile techniques have difficulties to deliver its services and applications. There are many different application scenarios where the proposed DTN routing protocols can be applied to solve the problem or improve the overall system performance. There are thus more applications possible than those presented in this thesis, leading to suggestions for future research as follows:

8.3.1 Space Communication and Navigation

As has been reviewed in Chapter 1 and Chapter 2, the preliminary design purpose of DTN systems is to tackle the issues of significant delays and data packet corruption in deep space communications [35]. In general terms, space communication refers to satellite communication systems [36] or satellite communication engineering [37]. However, in the last decade, there are some new cohorts have been deployed for space data transmission, such as tethered ultra-high altitude balloons [38] and UAVs [39].

Fig. 8-1 shows the basic space communication network architecture of Federated Satellite Systems [40]. Given the limitation of electromagnetic wave transmission distance and radio channel electromagnetic interference corruption in space, communication and navigation there can only be achieved in the SCF mode through the DTN space network. Normally, with the exception of the launch phase, satellites and other spacecraft travel in at steady speeds with small moving status changes, which satisfies the prerequisite of a LQG regulator for the KaFiR routing protocol. The KaFiR DTN algorithm has large potential opportunities for applications of space communication [47] and navigation [48].

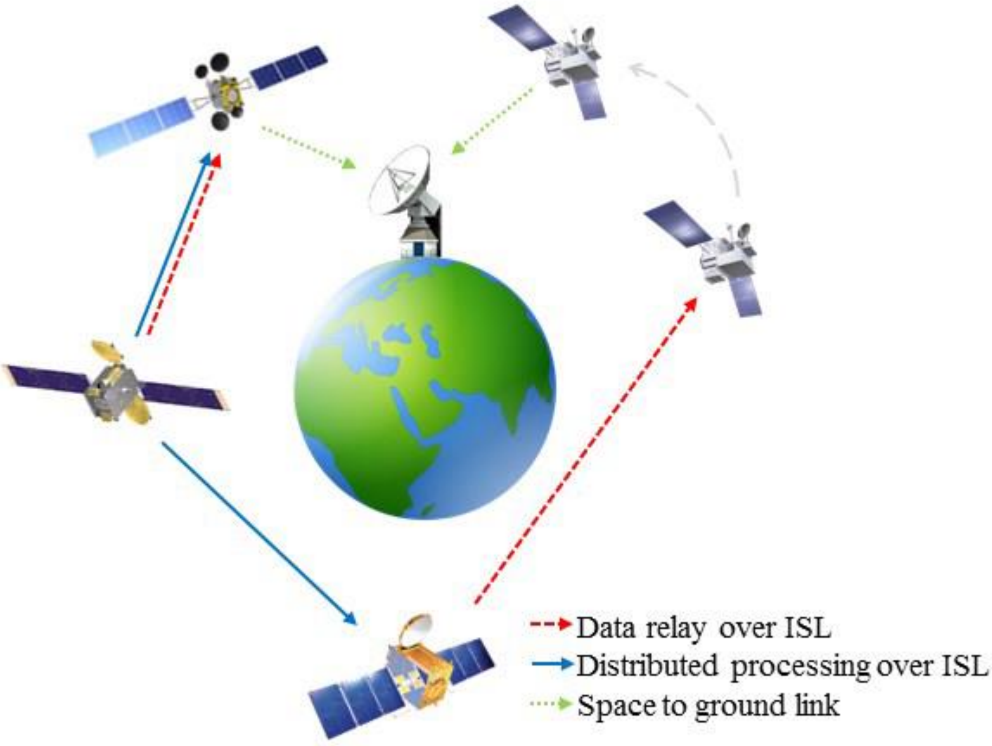

Fig. 8-1 FSS network architecture [40] (from Lluch et al., 2015).

The satellite network presented in Fig. 8-1 is a type of Low Earth Orbit (LEO) satellite communication system [41]. The large variety of satellites is defined in terms of orbit altitude, so other orbit satellites can be categorized as Medium Earth Orbit (MEO, also called Intermediate Circular Orbit (ICO)) [42], Geostationary Earth Orbit (GEO) [43], Highly Elliptical Orbit (HEO) [44], Polar Earth Orbit (PEO) [45] and Hybrid Satellite Orbit (HSO) [46]. For different satellite communication systems, the density of satellites exhibits significant differences, especially in ultra-high orbit satellite systems. A satellite has to wait for a long time to establish a bi-directional radio link with another satellite, which means the buffered message will suffer an extraordinary long time delay. In Section 3.4.1, the determination method of the routing strategy proposed a predefined threshold *n* to ensure that the packet is forwarded to a more reliable relaying node. For satellite communication networks, the value of threshold *n* should be designed carefully and based on network conditions that must be determined, otherwise, most data packets will be dropped.

8.3.2 Multi-Layer Network Flying Platform for NoF

In this thesis, the proposed PaFiR routing protocol only concentrated on the wireless system with a single aerial layer network flying platform for NoF. As the exponential service demands from subscribers mean that the mobile system will need to be expanded constantly, leading to a complex and expandable mobile system with a multi aerial layer network flying platform [49].

The advantages of the PaFiR relaying strategy equip it to cope with the complexity of such a system and endow the network with capability of resilience, tolerance and scalability.

8.3.3 Value Added Services

The proposed KaFiR and PaFiR routing protocols measure the movement of surrounding mobile subscribers to determine the relaying route of store and carrying data packets, so the relaying protocols provide opportunities to develop some value added services based on the observed and predicted location and speed information, for instance, positioning and location based services [50].

8.3.4 Dedicated DTN Systems

As has been reviewed in Section 2.1.1, there are some dedicated DTN systems designed for the particular applications, such as VDTN [51] for vehicular communications. To extend the advantages of the PaFiR relaying strategy to track and predict the movement of diversified moving objects, future work can optimize the optional function mentioned in Section 6.3.2. This will entail improving the self-adaptive function to adjust the number of particles applied for the filtering algorithm. This would enable bespoke applications to be developed and optimized, with vehicular networks being an immediate target.

8.3.5 Other Works

The researching work presented in this thesis shows that movement prediction technologies can help DTN routing protocols to improve the overall system performance. To the best of the author’s knowledge, comprehensive research of movement prediction technologies applying for DTN relaying strategy has just started. There are many movement reasoning techniques that can be applied for the forwarding algorithms. For the requirement from different wireless network applications, the appropriate prediction algorithm can be selected to build up the suitable relaying strategy, to achieve the best performance for the particular service system.

8.4 Security

Security is always one of the key issues of communication systems. For wireless networks, the majority of applications are operating in an open environment so implementation of security mechanisms is a significant challenge. In decentralized mobile systems, all smart portable devices form the network voluntarily and there is no complete and systematic security that can be implemented into the network directly. Tiwari and Veenadhari [52] reveal security issues and potential network attacking techniques of the DTN system, such as physical security, key management, routing and intrusion.

There are two of methods that can achieve security functions to secure the data transmission. Kate et al. [53] introduced a solution using an anonymous authentication protocol with identity based cryptography for DTN systems. However, security solutions deployed at the physical layer are more feasible. In 1975, Wyner had his pilot works on the physical layer security using wiretap channel for the initial point-to-point (P2P) transmission [54]. Multi-antenna technologies have been brought to the fore in the last decade. In [55], Li et al. introduced a secret communication by multi-antenna transmission. Khisti and Wornell used the MINOME (multi-input, multi-output, multi-eavesdropper) wiretap channel to achieve a secure transmission in DTNs [56]. The latest work published by Wang et al. [57] used multiple antennas to prevent pilot spoofing attack (PSA) or pilot jamming attack (PJA) and thus protect the information from leakage.

To implement security mechanisms in the DTN system, part of the throughput will be used to achieve the certain requirements of security. Zhou et al. presented a quantization framework to characterize the secure transmission efficiency [58].

8.5 Summary

The DTN technology is one of emerging research domains for the wireless communication which makes network systems independent from the existing or preset infrastructure. The proposed relaying strategies applied Bayesian filtering approaches to routing decision making to open new directions in this research area. These have led to various DTN networking solutions for different applications that include mobile IoT systems, UAVs assisted networks, flying network platforms, NoF and so on. These applications are all significant and popular research topics that show that the extension research and further work have a promising future.

In the chapter, the extension research on both KaFiR and PaFiR DTN routing protocols has been addressed. The extension research tasks will main concentrate on multiple modern filtering techniques which can either improve the accuracy of tracking and prediction or tackle some more complex application scenarios. The system performance in terms of resilience, tolerance and scalability can be increased constantly.

The future work part revealed some new applications that can deploy the proposed routing strategies into it to solve some difficulties. Technology innovation is the motivation of application development. The security issues and candidate solutions are discussed and identified in the final part.

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