Collaborative Networking: The Integration of Collaborative Communication into WSN-routing

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Zusammenfassung

Kabellose Sensornetze (WSNs) werden für viele verschiedene Anwendungsszenarien wie zum Beispiel Überwachung, Automatisierung und Gesundheit entwickelt. Die Sensorknoten messen bestimmte Parameter und übertragen ihre Daten kabellos zu einer zentralen Station für weitere Datenanalyse. Datenübertragung- und Vernetzungstechniken spielen eine wesentliche Rolle in WSNs, weil sie die Verbindung zwischen Sensorknoten realisieren und garantieren. Da kabellose Sensorknoten normalerweise klein, mobil und Ressourcen-begrenzt (bezogen auf Strom und Rechenfähigkeit) sind, haben sie eine beschränkte Übertragungsreichweite und verwenden einfache Datenübertragungstechniken. Außerdem werden sie von umgebenden Objekten blockiert oder wegen ihrer Mobilität isoliert. Alle diese Nachteile resultieren in einer niedrigen Effizienz der Datenübertragung, vor allem bezogen auf Zuverlässigkeit und Flexibilität.

In dieser Dissertation fokussieren wir auf kollaborative Kommunikation (CC) und entwickeln angemessene Lösungen für die oben genannten Probleme. Bei CC modifizieren eine Gruppe von Sensorknoten die Phasen ihrer Trägersignale und senden gemeinsam gleiche Signale zu bestimmten Zielknoten, sodass an diesen eine konstruktive Überlagerung von allen Signalen empfangen wird. Diese erhöhte Leistung ermöglicht eine bessere Qualität oder eine größere Übertragungsreichweite im Vergleich zu individueller Datenübertragung. Aufgrund der niedrigen Skalierbarkeit aktueller CC-Techniken sind diese jedoch in allen Netzen aus drahtlos kommunizierenden Knoten einsetzbar.

Als ersten Schritt analysieren wir die State-of-the-Art von CC-Techniken. Anschließend werden einige Verbesserungen bestehender Verfahren entwickelt und hiermit die ausgewählte CC-Technik modifiziert. Wir nennen das resultierende Verfahren CC+. Diese Methode hat eine bessere Energieeffizienz und Zuverlässigkeit. Dennoch ist CC+ schlecht skalierbar. Um dieses Problem zu lösen, integrieren wir CC+ mit zwei populären Networking-Techniken: Multi-Hop (MH) und Mobile WSNs (MWSNs).

Bei MH nehmen eine Reihe von zwischenliegenden Knoten in die Datenübertragung zwischen Quell- und Zielknoten an dem Datenübertragungsprozess teil. MH-CC, die durch Integration von CC+ und MH, verwendet im Vergleich zu normalem MH bestimmte Quell- und Zielknoten mit weniger Relays was zu einem einfacheren Routing-Prozess führt. Die Daten können auch nach dem Deaktivieren einiger Sensorknoten übertragen werden, jedoch bei niedrigerer Qualität. Hierdurch ermöglicht MH-CC eine erhöhte Zuverlässigkeit der Datenübertragung in WSNs. Außerdem hat sich herausgestellt, dass der Übertragungsbereich von CC+ von der Anzahl kollaborativ sendender Knoten sowie der Genauigkeit der Synchronisation abhängt. Daher kann MH-CC flexibel und effizient die Topologie-Veränderung durch

Knoten-Mobilität ausgleichen.

MWSN ist eine andere Networking-Technik für ressourcenbeschränkte WSNs. In MWSNs gibt es zwei verschiedene Typen von Knoten: Sensorknoten die Daten produzieren und Mobilknoten, die sich durch ein WSN-Gebiet bewegen und die Daten von Sensorknoten erfassen. Der Datenerfassungsgrad ist der Prozentsatz von Sensorknoten dessen Daten schon erfasst sind und hängt von der Zahl und dem Mobilitätsmuster von Mobilknoten sowie die Übertragungsbereich von Sensorknoten ab.

Ein begrenzendes Problem in MWSNs ist die Implementierung und Instandhaltung der Mobilknoten. Besonders in erweiterten Szenarien wie Stadtweiten-Messungen werden bestehende Mobile Objekte (wie Taxis) als Mobilknoten verwendet und tragen geeignete Sendeempfänger. Diese Idee ist sehr kosteneffizient, allerdings sind die Mobilitätsmuster von Taxis nicht optimal für die Datenerfassung. Besonders Sensorknoten in großen Parks oder im Stadtrandgebiet besuchen die Mobilknoten so selten, dass ihre Daten bereits veraltet sind. Eine genaue Analyse zeigt auch, dass die Zahl der Taxis oder die Übertragungsreichweite von Sensorknoten keine Lösung darstellen. Alternativ entwickeln wir eine neue Version von CC und integrierten es mit MWSN. Basierend auf der neuentwickelten CC-MWSN-Variante werden Sensorknoten in bestimmte Cluster gegliedert und benutzen CC im Empfangs-Modus um ihre Umgebung zu Scannen. Sobald ein Mobilknoten detektiert wird, nutzen Sensorknoten CC im Sende-Modus für die Datenübertragung. Da die Eigenschaften der CC-Technik vor der Entwicklung des WSN festgestellt werden müssen, analysieren wir auch den optimalen Übertragungsbereich für CC-MWSN.

Abstract

Wireless Sensor Networks (WSNs) are deployed in a variety of application scenarios, including surveillance, automation, smart environments, and healthcare, to sense, measure, and monitor certain parameters, and report their measurements and readings to a base station. Data communication and networking techniques play key roles in WSNs, as they realize and maintain the network connectivity. Wireless sensor nodes, characterized mostly as small-sized, resource-restricted, and battery-powered, have relatively short transmission range, are blocked easily by surrounding objects, and due to their low computational power apply simple data communication techniques. All of these shortcomings and drawbacks result in a relatively low performance of data communication, particularly in terms of reliability and flexibility, which consequently limits the WSNs' applications severely.

In this thesis, the focus is placed on the Collaborative Communication (CC) techniques, and appropriate solutions for the above-mentioned inadequacies are proposed. According to the CC, a group of sensor nodes modify their carrier phases, so that their signals are received by the destination synchronously. Therefore, if all of the nodes send the same signal simultaneously, the destination receives a constructive combination of their multiple signals. The increased power level at the destination, thus, improves the signal quality and allows the nodes to potentially communicate with a farther destination. However, the existing CC approaches are not capable of being deployed in extended WSN applications, due to their low efficiency and scalability.

As the first step, a review of the state-of-the-art on the CC methods is presented, followed by a declaration of the required features of an 'ideal' CC technique to match the WSNs. One of the investigated existing CC approaches, which has a higher potential to fulfill these requirements, is then selected. A series of modifications and improvements on the selected approach is performed, and it is then highlighted how the modified CC technique (referred to above as 'ideal') is now capable of providing a trade-off between varying levels of energy efficiency and reliability. Furthermore, it is demonstrated that this modified CC technique is capable of autonomously adapting to different network design objectives.

Although the resulting CC approach has a relatively high performance, its application is still limited to small scale networks. In order to solve this problem, we integrate it with the two of the most widely-used networking approaches: Multi-Hop (MH) and Mobile WSNs (MWSNs). In multi-hop networking, a path of intermediate nodes connects the source to the destination by relaying its messages. As the result of the integration of CC with MH, MH-CC technique is capable of extending the transmission range of the relay nodes along the path between source and destination, which results in a simpler routing approach. In addition, signal is transmitted by a group of nodes, therefore the

failure of one or a few of which does not lead to link break and interruption of data communication. Since the transmission range varies potentially as a function of the number of nodes which participate in CC, MH-CC is able to flexibly modify the length of hops in order to e.g. jump over inappropriate relay nodes. Moreover, multi-metric approaches are applied to empower MH-CC to autonomously adapt to the topological changes due to dynamic situations.

MWSN is another efficient networking approach which highly suits resource-restricted WSNs. In MWSNs, mobile nodes move all around the network to collect the acquired data of sensor nodes. The data collection rate (percentage of the data collected within a certain period of time) depends on the number and the mobility pattern of mobile nodes as well as the transmission range of sensor nodes. However, especially in extended scenarios such as urban sensing, appropriate transceivers are attached to the existing mobile objects (e.g. Taxis in urban sensing scenarios) and act as mobile nodes. Despite of the cost efficiency of this idea, the mobility pattern of such mobile nodes cannot be optimized for data collection approach. Therefore sensor nodes in the suburbs or large parks might be aggregated with relatively long delays, which might compromise their validity. Analyses show that even increasing the number of mobile nodes or the transmission range of sensor nodes are not efficient solutions. CC is applied in this research scenario to solve this problem. According to the new technique, dubbed CC-MWSN, sensor nodes grouped in clusters use CC both to search for the mobile nodes and to transmit their data. In addition, the Optimum Transmission Range (OTR) of the sensor nodes to gain a specific data collection rate is achieved.

Contents

1 Introduction **1**

1.1 Problem Definition . . . 1

1.1.1 Low Reliability . . . 2

1.1.2 Low Flexibility . . . 2

1.2 Proposed Solution: Collaborative Communication . . . 2

1.3 Research Approach . . . 3

1.4 Inadequacies of the Existing CC Techniques . . . 6

1.4.1 Lack of an Appropriate Approach to Find Suitable (Local) Destination . . . 7

1.4.2 Lack of Appropriate Metrics to Select Suitable C-nodes 7

1.4.3 Inability to Adapt to Topology Changes or Network Design Objectives . . . 8

1.4.4 Low Capability to Extend Transmission Range . . . 8

1.5 Research Methodology . . . 8

1.6 Publications . . . 9

1.7 Organization of the Thesis . . . 10

2 Background Information **13**

2.1 Wireless Sensor Networks . . . 13

2.1.1 Sensor Nodes . . . 13

2.1.2 Network Topology . . . 16

2.1.2.1 Flat . . . 16

2.1.2.2 Clustered . . . 16

2.1.3 Data Communication Techniques . . . 17

2.1.3.1 Direct Communication . . . 17

2.1.3.2 Hierarchical Communication . . . 17

2.1.3.3 Multi-Hop Communication . . . 18

2.1.3.4 Mobile WSNs (MWSN) . . . 18

2.2 Collaborative Communication (CC) in WSN . . . 20

2.2.1 Beamforming . . . 20

2.2.2 Collaborative Communication for Transmit Mode (CC-T) . . . 20

2.2.3 Frequency Synchronization for CC-T . . . 23

2.2.4 Phase Synchronization in CC-T . . . 25

2.2.4.1 Full-Feedback Closed-Loop . . . 27

2.2.4.2 Time-Slotted Round-Trip Carrier Synchronization . . . 27
2.2.4.3 One-Bit Feedback Closed-Loop (OBCL) . . . 28
2.2.4.4 (1+1)-Evolutionary Algorithm . . . 30
2.2.4.5 Master-slave open-loop . . . 31
2.3 Routing in WSNs . . . 33
2.3.1 Methods of Categorizing the Routing Protocols . . . 34
2.3.2 Appropriate Routing Objectives to be Applied in WSNs Applications . . . 35
2.3.3 State of the Art of Routing Protocols in WSNs . . . 36
2.3.3.1 Flooding and Gossiping . . . 36
2.3.3.2 Sensor Protocols for Information via Negotiation . . . 37
2.3.3.3 Directed Diffusion . . . 37
2.3.3.4 Low Energy Adaptive Clustering Hierarchy . . . 38
2.3.3.5 Geographic Adaptive Fidelity . . . 38
2.4 Mobile Wireless Sensor Networking . . . 39
2.5 Summary . . . 41

3 Collaborative Communication (CC) 43
3.1 Major Features of the Appropriate CC Approach . . . 43
3.1.1 Flexibility . . . 44
3.1.2 Energy Efficiency . . . 44
3.1.3 Distributed Structure . . . 44
3.1.4 Autonomous Activity . . . 45
3.2 Suitable Existing CC Approach . . . 45
3.3 Collaborative Communication at Receive Mode (CC-R) . . . 46
3.3.1 CC-R Platform . . . 50
3.3.1.1 Initialization . . . 51
3.3.1.2 Synchronization . . . 51
3.3.1.3 Aggregation . . . 52
3.4 Performance Evaluation . . . 54
3.4.1 Comparison of CC-R to CC-T . . . 54
3.4.2 Impact of CC on Transmission Range . . . 55
3.4.3 Minimum Number of C-nodes . . . 56
3.4.4 Energy Consumption . . . 60
3.4.4.1 Initialization . . . 60
3.4.4.2 Synchronization . . . 60
3.4.4.3 Aggregation . . . 61
3.5 Collaborative Channel Equalization . . . 61
3.5.1 Signal and Channel Model . . . 62
3.5.2 Least Square Constant Modulus Algorithm . . . 63
3.5.3 Performance Analysis of Collaborative Channel Equalization . . . 63

3.6 Experimental Analysis . . . 65
3.6.1 Scenario . . . 65
3.6.2 Experimental Results . . . 67
3.6.2.1 Signal Quality . . . 67
3.6.2.2 Reliability . . . 67
3.7 Ideas for Adaptive Improvement of the CC Performance . . . 68
3.7.1 Application of Effective Factors to CC . . . 69
3.7.1.1 Ranking of the Potential C-nodes . . . 70
3.7.1.2 Selection of the Minimum Number of C-nodes 70
3.7.1.3 Performance Analysis . . . 72
3.7.2 Regulation of the Energy Consumption . . . 74
3.8 Summary . . . 75

4 Multi-Hop Collaborative Communication (MH-CC) 77
4.1 Impact of MH-CC on Sensor Nodes' Activity . . . 78
4.2 Challenges Behind MH-CC Routing . . . 80
4.3 MH-CC Routing . . . 81
4.3.1 Route Discovery . . . 82
4.3.2 Route Correction . . . 83
4.3.3 Data Transmission . . . 85
4.3.4 Route Maintenance . . . 85
4.3.4.1 The Failure of a CR-node . . . 87
4.3.4.2 C-node Failure . . . 89
4.3.4.3 The Failure of a Standby Node . . . 90
4.3.4.4 The Mobility of C-nodes or CR-nodes . . . 90
4.4 Desired Characteristics of Routing in MH-CC . . . 91
4.4.0.5 Re/Proactivity . . . 91
4.4.0.6 Route Discovery Approach . . . 91
4.4.0.7 Network Structure . . . 91
4.4.0.8 Location Awareness . . . 91
4.5 Performance Evaluation of the Routing Approach . . . 92
4.5.1 Optimum Level of Synchronization Quality . . . 92
4.5.2 Optimum Setting of MH-CC in Terms of Energy Efficiency . . . 96
4.5.3 Reliability Analysis . . . 98
4.6 Multi-Metric MH-CC . . . 101
4.6.1 Multi-Metric Approach to Discover MH Path . . . 102
4.6.2 Multi-Metric Approach to Select CR-Node . . . 102
4.6.3 Multi-Metric Approach to Select C-nodes . . . 102
4.7 Summary . . . 103

5 Collaborative Communication in Mobile WSNs 105
5.1 Problem Statement . . . 105

5.2 Solution: Application of Collaborative Communication in MWSN . . . 108
5.3 CC-MWSN Algorithm . . . 110
5.3.1 Initialization . . . 110
5.3.2 Scanning . . . 111
5.3.3 Data Transmission . . . 111
5.4 Appropriate CC Approach to Apply to CC-MWSN . . . 113
5.5 Optimal Transmission Range (OTR) . . . 113
5.5.1 OTR for Random Walk Mobility Model . . . 114
5.5.1.1 OTR for one cluster ($N = 1$) . . . 114
5.5.1.2 OTR for more than one cluster ($N > 1$) . . . 115
5.5.2 OTR for Random Waypoint Model . . . 116
5.5.2.1 OTR for one cluster ($N = 1$) . . . 117
5.5.2.2 OTR for more than one cluster ($N > 1$) . . . 118
5.5.3 Comparison of OTR for the Investigated Mobility Models 119
5.6 Experiments on Beijing Taxi Trajectories . . . 122
5.7 Summary . . . 124

6 Summary, Conclusion, and Potential Future Directions 125
6.1 Contributions . . . 125
6.1.1 CC+: A High Performance CC Approach . . . 125
6.1.1.1 CC in Receive Mode (CC-R) . . . 126
6.1.1.2 Development of Flexibility and Autonomy in CC . . . 127
6.1.2 Integration of CC to Multi-Hop Routing . . . 128
6.1.3 Application of CC in Mobile WSNs (CC-MWSN) . . . 128
6.2 Fulfilled Research Questions . . . 129
6.2.1 Reliable Data Communication . . . 130
6.2.2 Flexible Data Communication . . . 130
6.2.3 Autonomous Data Communication . . . 130
6.3 Potential Directions for Further Extension . . . 130
6.3.1 Development of MAC Layer Techniques Compatible with CC . . . 131
6.3.2 Integration of CC into Location-Aware WSNs . . . 131
6.3.3 Development of Autonomy and Flexibility in CC-MWSN 132

Bibliography 133

Eigene Veröffentlichungen 141

Chapter 1

Introduction

Wireless Sensor Network (WSN) is one of the key enabling tools for future smart environments and ambient intelligence. The constituent elements of WSNs, wireless sensor nodes, operate in the background and are arranged in an infrastructure-less and distributed fashion. They can be deployed everywhere and sense various parameters, process them and provide services which could potentially improve human life in various aspects, e.g. social activity, healthcare, home and office automation, and transportation, to name a few.

Technological advances in areas such as RFID design, printed and Nano-electronics will in the near future lead to the realization of the wide application of micro-sized sensor nodes costing only a few cents. These tiny nodes will be distributed in a wide range all around us; in supermarkets to guide the customers and provide them with information about different goods; in the office and home for automation; and even inside cloths to measure and monitor vital bio-signs for health-related applications. Although such nodes can be deployed with high density, there would be restrictions in terms of computational power, battery capacity and communication sub-systems.

1.1 Problem Definition

One of the major tasks of sensor nodes which has a high impact on the performance of WSNs is data communication and networking. It maintains the connectivity of sensor nodes and guarantees efficient data delivery. In order to match WSNs to real-world applications, reliability and robustness are the two vital features to consider. In addition, in some of the above-mentioned applications, the network topology considerably varies over time. Therefore, communication techniques should be able to compensate for the topological changes autonomously. Regarding the resource restriction and vulnerability of the sensor nodes, the development of an appropriate data communication approach is a challenging issue. The major problem would be the low reliability and flexibility of data communication which can degrade the performance of WSNs.

1.1.1 Low Reliability

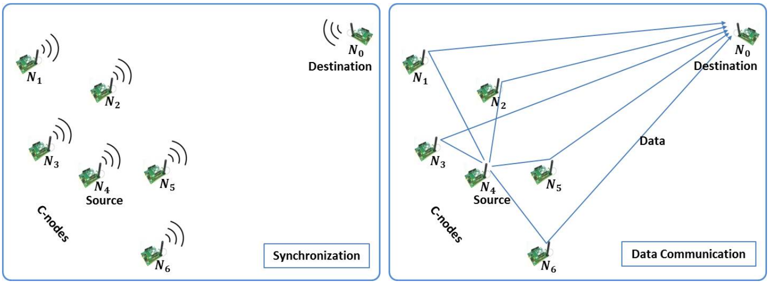
Wireless sensor nodes are mobile and have relatively short transmission range. Thus, even small movements might disconnect them from their neighbors. Furthermore, since compared to their surrounding objects sensor nodes are quite small, they can be easily blocked or defected. Due to the lack of appropriate memory and processing power, data cannot be buffered at the sensor nodes. Therefore, in the case of blockage or disconnection, the measured data will be overwritten. Such a low reliability in intra-node interactions directly affects the reliability of data communication and networking in the entire network. Especially, in multi-hop networks the problem would be more critical since the multiple links along the path between source and destination should properly work to deliver the message. It causes a limited reliability in terms of networking and data communication in WSNs.

1.1.2 Low Flexibility

The mobility of sensor nodes and their surrounding objects could change the network topology (relation of the nodes) continuously. Hence, considering a certain area in a WSN, the density of the nodes varies over time. However, depending on the transmission range of the nodes, the available channels and the desired connectivity, there is an optimum value for the density of the nodes. Lower density results in weak connectivity whereas higher density would lead to channel scarcity, because of the increasing of the number of sensor nodes which would request free channels whereas the number of available channels is usually fixed. In addition, the WSN's objectives in terms of networking and data communication might vary over time. For instance, network objectives when sensor nodes are reporting temperature values in a normal range would be different from when they are reporting values referring to fire or critical situations. In the first case, energy efficiency has the highest priority. In the case of a fire however, the maximum delivery rate with high reliability would be the first priority. Therefore, sensor nodes should be able to autonomously modify data communication techniques to compensate topology changes or adapt to different situation-based network objectives.

1.2 Proposed Solution: Collaborative Communication

Collaborative Communication (CC) is a data communication technique which is able to improve both the reliability and flexibility of data communication in WSNs. As seen in figure 1.1, a message is sent by a group of collaborative nodes (C-nodes). C-nodes set their carrier phases so that their multiple signals are received by the destination synchronously. Compared to



(a) Synchronization step: appropriate phase shifts for C-nodes are achieved

(b) C-nodes modify their carrier phases and relay the signal of the source simultaneously through the destination

Figure 1.1: Single-hop collaborative communication

the case of individual communication, the destination receives the message at a higher quality level. Therefore, the destination can be located at a farther distance. The transmission range extension of CC directly depends on the number of C-nodes and the synchronization accuracy. Thus, it can be autonomously controlled by sensor nodes to compensate topological changes or to match to different network design objectives. In addition, since a common signal is sent by a group of C-nodes, CC improves the reliability. Therefore, in the case of blockage or disconnection of some of the nodes, the message is still delivered, but at a lower quality due to the decreasing of the number of C-nodes.

Although CC is potentially capable of improving networking and data communication in WSNs, existing techniques provide low efficiency. In addition, current approaches only work in the single hop scenario (figure 1.1). Therefore, CC can be applied as a starting point to develop an appropriate data communication and networking approach. This forms the foundation of our proposed solution.

1.3 Research Approach

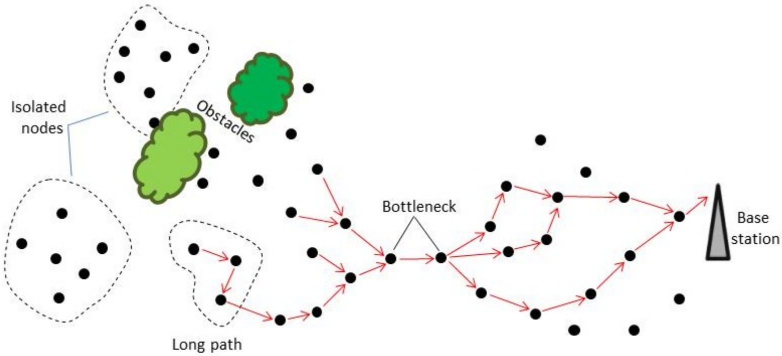
The main objective of this thesis is to develop a highly reliable and flexible data communication and networking technique which suits extended WSNs. For this we propose the integration of collaborative communication with appropriate networking techniques, including Multi-Hop (MH) and Mobile WSNs (MWSN). The main features of the resulting techniques are, therefore, as follows:

- **Higher level of flexibility in networking:** Transmission range can be modified by controlling the number of C-nodes and the accuracy of synchronization. Sensor nodes match to the expected network topology by the modification of their transmission range.
- **Higher level of reliability:** A certain message is transmitted by a group of nodes, therefore missing of one or a few of them does not lead to link break.
- **Higher level of network connectivity:** CC empowers sensor nodes to extend their transmission range and connect to destinations that are normally out of their coverage area and in the case of individual (non-collaborative) communication are inaccessible.
- **Regulated energy consumption:** Each message is communicated using a group of nodes and the workload is then shared among the entire nodes.
- **Higher level of autonomy:** Sensor nodes are capable of matching to different network design objectives through controlling the settings of CC.
- **Higher level of robustness:** Topological changes due to dynamic situations are compensated.

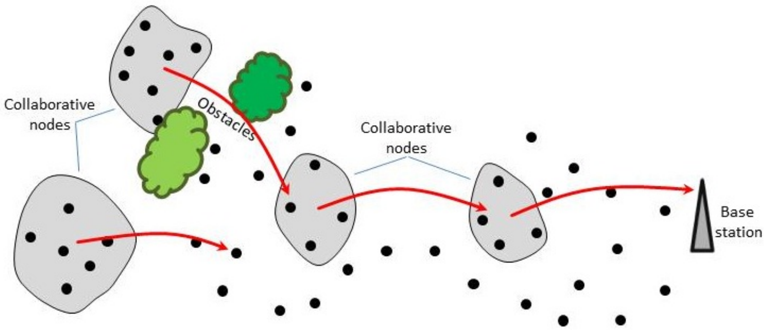
Figure 1.2 compares data communication in a WSN in two cases of standard MH and MH-CC - the integration of MH and CC. In the case of MH (figure 1.2(a)), weak network connectivity is observed: network is split, bottlenecks decrease the network delivery rate and rapidly exhaust the resources of some nodes. Moreover, messages of remote nodes are delivered through a large number of relays. All of these effects degrade data communication performance in terms of reliability, robustness and flexibility.

The application of CC enhances the networking performance. As illustrated in figure 1.2(b), even messages of remote nodes are delivered within few relays which efficiently decrease the routing complexity and improve reliability. In addition, a relay with higher transmission range would solve the bottleneck problem, i.e. potential bottlenecks can be easily jumped over. Furthermore, the improved network connectivity decreases the probability of isolation or packet loss due to link breakage or blockage.

CC affects the MWSNs in a similar way. In these networks, mobile nodes move all around the sensing field and collect the data of sensor nodes by approaching them. Especially in those cases that mobile nodes are not originally deployed for data collection (e.g. Taxis equipped with specific transceivers which are applied for urban sensing), sensors that belong to some areas like suburb or large parks would relatively have lower chance to be met by mobile



(a) Conventional multi-hop



(b) MH-CC

Figure 1.2: Comparison of the quality of data communication in cases of MH and MH-CC

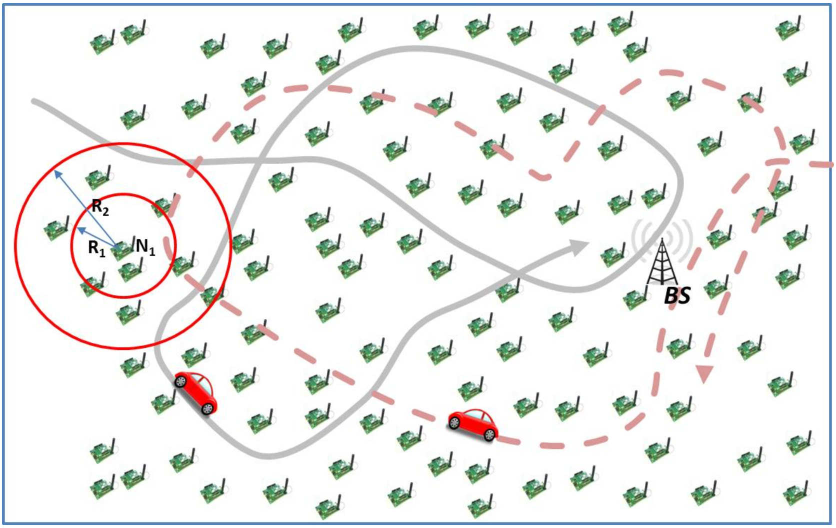


Figure 1.3: Illustration of the positive effects of CC on the network connectivity of MWSNs

nodes. Surrounding obstacles might partially block the sensor nodes which would even further decrease their chance. The integration of CC and MWSN, dubbed CC-MWSN, efficiently improves the network connectivity, flexibility and autonomy by the adaptive variation of the transmission range of the sensor nodes.

Figure 1.3 illustrates the positive effect of CC-MWSN of the data collection rate. In this figure, R_1 and R_2 are the transmission range in the cases of individual and collaborative communication, respectively. Considering specific paths for mobile nodes, in the case of MWSN, the data of sensor node N_1 is collected only one time. However, in the case of CC-MWSN, this node meets the mobile nodes more often. It is worth noting that CC-MWSN is different from the extension of the transmission range of individual nodes. Because in that case, each node needs a specific channel which might result in channel scarcity. However, in CC-MWSN, the entire C-nodes use the same channel to send data to a specific destination.

1.4 Inadequacies of the Existing CC Techniques

Despite of great efforts to enhance the performance of CC, existing techniques do not allow for the extension of CC in large-scale WSNs. It is mostly due to either the inefficiency of CC or lack of appropriate features to be integrated in networking approaches. In the following sections, these shortcomings are mentioned in detail.

1.4.1 Lack of an Appropriate Approach to Find Suitable (Local) Destination

In existing works, the destination is known and accessible for C-nodes in advance. Therefore the only tasks to realize CC are synchronization and data communication. However in MH-CC, several CC sessions are needed to connect a specific pair of source and destinations. At each session, C-nodes should discover an appropriate local destination which is in the direction of the final destination.

Assuming a new CC approach which extends the transmission range efficiently, the problem is more challenging. Following the standard rout discovery algorithms, C-nodes should firstly detect the entire potential local destinations, rank them based on their closeness to the final destination and then select the optimum one. However, depending on the number of C-nodes, there are lots of potential local destinations which are not accessible for C-nodes before collaboration. It is in the case that before fixing of the local destination, C-nodes are unable to setup collaboration and extend their transmission range.

1.4.2 Lack of Appropriate Metrics to Select Suitable C-nodes

This problem reduces the efficiency of the existing CC approaches as well. Various factors like transmission channel effects, obstacles and different workloads might change the capability of the potential C-nodes to participate to the collaboration. Obviously, the selection of highest quality C-nodes would result in a higher signal quality at the destination. On the other hand, at each CC session there is an optimum number of C-nodes to gain the required signal quality at the destination. The participation of higher number of C-nodes results in an increase in the energy consumption and the complexity of CC whereas fewer C-nodes would lead to low signal quality at the destination. Therefore, one necessary criterion would be to establish appropriate metrics to determine optimum setup for CC in an autonomous way.

1.4.3 Inability to Adapt to Topology Changes or Network Design Objectives

As mentioned before, CC is able to control the transmission range as well as network reliability by modification of the number of C-nodes and the synchronization accuracy. However, in none of the existing approaches this feature is taken into account.

1.4.4 Low Capability to Extend Transmission Range

Almost all of the existing CC techniques are based on individually communication of the C-nodes with the destination for synchronization. Therefore, the destination and remote node should be in the transmission range of each other. However, in order to realize MH-CC a CC approach with the capability of transmission range extension is required.

1.5 Research Methodology

Figure 1.4 shows the procedures considered for achieving the goals and objectives of this thesis. They include:

- **Scenario and Problem Statement**

  The first step would be to define the scenario and state the problems. In this research, an extended WSN composed of resource restricted sensor nodes is considered. The major inadequacies of such networks are the low reliability and flexibility of data communication and networking. As a solution for these problems, the integration of CC into networking techniques in WSNs is proposed and the two of the widely used networking techniques MH and MWSN are selected.

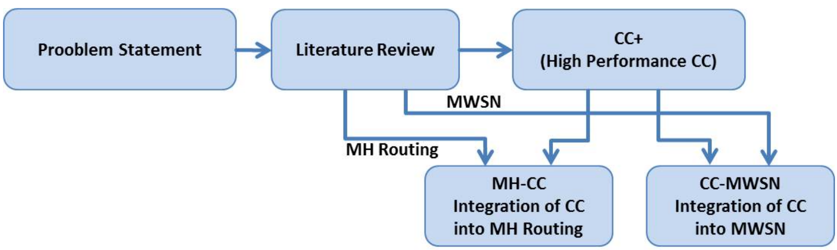


Figure 1.4: Research methodology and structure of the thesis at a glance

- **Literature review and related work**

  Our scenario determines which of the existing CC approaches has the most potential capability to solve the above-mentioned problems. After a review of the existing CC techniques, a suitable one as the starting point is selected. In addition, networking approaches in WSN applications are briefly reviewed as well.

- **Design and development of appropriate CC technique (dubbed CC+) for integration with the networking approaches**

  There are a number of differences between our scenario and the scenarios based on which most of the existing CC techniques are developed. Therefore, a necessary precursor is to modify the selected CC approach and to match it to our scenario.

- **Integration of CC+ to networking techniques to extend the application of CC to large-scale networks**

  In this step, the main idea of this thesis is implemented. We propose two different approaches for the extension of the application of CC to large-scale WSNs, both of which are based on the fusion of CC into networking techniques. We focus on two families of multi-hop and mobile WSN techniques, and then subsequently develop appropriate solutions to merge them into CC.

- **Optimization of the developed techniques for the integration of CC to routing approaches**

  Some of the challenges of CC are those regarding unclear metrics to select high quality C-nodes for collaboration. In this step, we address this problem and define metrics which would enable sensor nodes to estimate their effectiveness for collaboration. In addition, multi-metric approach is applied to adapt the MH-CC and CC-MWSN characteristics to the topological changes or various networking objectives e.g. high reliability or energy efficiency.

1.6 Publications

1. **Behnam Banitalebi** and Michael Beigl, MH-CC: multi-hop collaborative data communication in WSNs, International Symposium on Personal Indoor Mobile Radio Communication (PIMRC), 2013, London-UK.

2. Qiao Fu, **Behnam Banitalebi**, Lin Zhang, Michael Beigl, Energy-efficient collaborative data collection in mobile wireless sensor networks, Annual Conference on Information Sciences and Systems (CISS), 2013, Baltimore-Maryland.

3. **Behnam Banitalebi**, Michael Beigl, Transmission channel sensitive multi-metric routing for WSNs, International Conference on Wireless Communications in Unusual and Confined Areas (ICWCUCA 2012), 2012, Clermont ferrand-France.

4. **Behnam Banitalebi**, Yong Ding, Hedda R. Schmidtke and Michael Beigl, Channel allocation modification for emergency situations in IEEE 802.11 DCF based ad-hoc networks, International Conference on Networked Sensing Systems (INSS 2012), 2012, Antwerp-Belgium.

5. **Behnam Banitalebi**, Michael Beigl, and Rayan El Masry, A realistic hop-cost model for distance vector routing in ad-hoc wireless sensor networks, International Conference on Networked Sensing Systems (INSS 2012), 2012, Antwerp-Belgium.

6. **Behnam Banitalebi**, Dawud Gordon, Stephan Sigg, Takashi Miyaki, and Michael Beigl, Collaborative channel equalization: analysis and performance evaluation of distributed aggregation methods in WSNs, IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS'11), 2011, Valencia-Spain.

7. **Behnam Banitalebi**, Takashi Miyaki, Hedda R. Schmidtke, and Michael Beigl, Self-optimized collaborative data communication in wireless sensor networks, ACM workshop Organic Computing as part of ICAC 2011, 2011, Karlsruhe-Germany.

8. **Behnam Banitalebi**, Stephan Sigg, and Michael Beigl, Performance analysis of receive collaboration in TDMA-based wireless sensor networks, International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (Ubicomm 2010), 2010, Florence-Italy.

9. **Behnam Banitalebi**, Stephan Sigg, and Michael Beigl, On the feasibility of receive collaboration in wireless sensor networks, IEEE International Symposium on Personal Indoor Mobile Radio Communication, 2010, Istanbul-Turkey.

1.7 Organization of the Thesis

The structure of this thesis is represented in figure 1.5. In chapter 2, essential background and state of the art of CC and networking approach in WSNs, including multi-hop and mobile WSNs (MWSN) are reviewed. The remain-

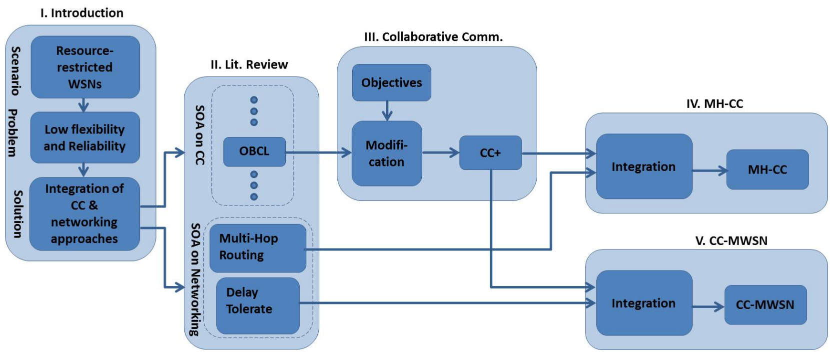


Figure 1.5: Research methodology and structure of the thesis in detail

der of the thesis represents the results of the research work and experiments accomplished by the author. In chapter 3, starting from one of the existing approaches, a suitable CC approach (referred to as CC+) is developed to integrate to networking techniques. In chapter 4 and 5, the extension of the CC applications in large-scale networks is considered. Two novel techniques, called MH-CC and CC-MWSN, are developed which enable multi-hop and MWSN networks to exploit CC for the enhancement of reliability and flexibility. Finally, in chapter 6, achievements of this research as well as possible ways to further extend this work are summarized.

Chapter 2

Background Information

In this chapter, the essential background knowledge required to improve the flexibility and reliability of data communication in WSNs is reviewed. According to the previous discussion in chapter 1, the most suitable solution is the development of the application of collaborative communication (CC) to large-scale WSNs via the integration of CC to networking techniques. Therefore, this work spans at least three major domains: the principles of WSNs, CC and networking approaches in WSNs.

2.1 Wireless Sensor Networks

An explicit review of WSNs is presented in [Sta08b], [AV10], [SMZ07], and [CES04]. WSNs are infrastructure-less networks of wireless units (sensor nodes) equipped with appropriate sub-systems to sense, measure and report specific kinds of environmental parameters. Such a general definition makes their application range quite wide including medicine [STA+08a] [SC06] and healthcare [JEZ+05], retail store [GBI09], traffic control [DBMB12], battlefield [WTK11], habitat monitoring [ZSLM04] amongst others. Due to these diverse applications, different kinds of sensor nodes, sensing and processing techniques, as well as data communication and networking approaches have been developed. In this section, only those aspects of WSNs which are exploited in this work are discussed.

2.1.1 Sensor Nodes

Sensor nodes are the building blocks of WSNs. Their major tasks include sensing, measuring, and reporting certain kinds of parameters to a destination. The destination can be a simple sensor node, a base station which gathers sensor data for further analysis, or a control system which uses this data to control other systems, e.g. air conditioning system which is controlled based on the data received from temperature sensors. Figure 2.1 shows a typical structure of a sensor node that is composed of the following units:

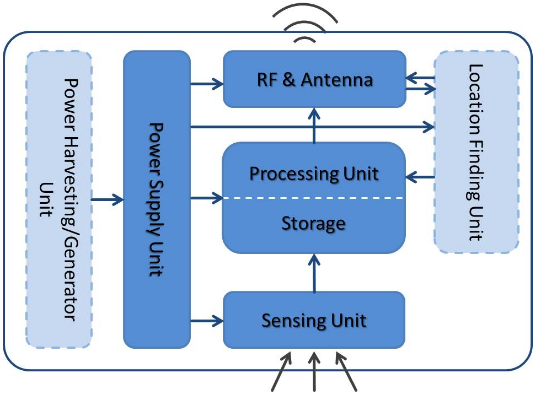


Figure 2.1: A view of a typical sensor node

- **Sensing Unit**:

  Sensor nodes use a wide range of sensors to sense [AV10]: temperature, humidity, pressure, speed, light, (electrical/acoustic) noise level, direction, movement, etc. Depending on the target application, special sorts of sensors are installed in the sensor nodes. The sensing unit is controlled by the processing unit to work either continuously or periodically. As a result of the high variety of sensors, there are various applications of WSNs.

- **Processing and Memory Units**:

  In the simplest case, the processing unit receives raw data from the sensing unit and organizes it into appropriate packet formats (splitting the data into a specific length, adding management bits such as header, address, etc.). Particularly, when the sensing unit generates large amounts of data, the processing unit pre-processes it in order to reduce the data redundancy. For instance, in the case of vision-based surveillance WSNs, the sensing units capture and send video streams to the processing unit. In the case of centralized processing, collection of the data of sensor nodes to a central power processor would be quite resource-demanding. However, in the case of pre-processing, the results of analysis or at least specific parts of the captured video streams are sent to the destination [MV12].

  In addition, this unit processes data that is received by RF unit. There are different types of messages that a sensor node might receive; e.g. commands to stop or start a sensing activity, routing messages, and messages which should be relayed. The processing unit detects the type of messages and decides on how to manage them. In [AV10], the processing capability is evaluated using the CPU speed, programming memory and RAM capacity. For commercial sensor nodes, CPU speed is in the range of $8 - 266\ MHz$, programming memory varies between $8\ KBits$ and $8\ MBits$ and RAM capacity varies between $0.5\ KBits$ and $32\ MBits$.

- **RF and Antenna Unit**:

  Sensor nodes communicate with each other via RF and antenna units. The RF unit is connected to the processing unit and receives certain bit streams and prepares them for transmission. The preparation stage includes modulation, up-conversion, amplification and transmission. In the case of coherent data communication, the RF module is responsible for interaction with the other nodes for adjusting their carrier frequencies. Theoretically, any of the modulation techniques can be applied to the sensor nodes. However, in order to maintain high energy efficiency, certain kinds of modulation techniques are preferred which are discussed in [SBS08] and [APM04]. These units are also responsible for data reception. They receive, down-convert and de-modulate the impinging signals and send the resulting bit streams to processing unit.

- **Power Supply Unit**:

  This unit is responsible for providing the power needed to drive other sub-systems. In most applications, non-rechargeable batteries are used in sensor nodes. Low cost sensors operate during their life-time and after the exhaustion of their batteries they will be deactivated forever. On the other hand, there are other kinds of sensor nodes whose batteries are rechargeable or can be replaced. Such sensor nodes are usually deployed manually in relatively small networks and specifically in the areas such as indoor environments they are easily accessible.

Optional Units:

- **Location Finding Unit**:

  Location information deeply influences the sensor nodes' activity. Specifically in terms of networking and data communication, sensor nodes know which of their neighbors can relay their signals to the destination. Therefore, they would have simpler routing approach.

  There are different methods for providing location information. The application of Global Positioning System (GPS) to find the position of nodes is the simplest way. However, GPS modules need the signal of multiple satellites for location finding. Therefore, this method is mostly applied in outdoor scenarios [HSBH^{+}09], [JBKR08]. Another method which highly matches to indoor applications is triangulation [FAVZ12]. According to this method, specific indicators broadcast certain signals to the sensor nodes. Sensor nodes find their location by comparison of the time delay among the signal of indicators. It is proved that if a sensor node receives the signal of at least 3 indicators it is able to find its position.

- **Power Harvesting/Generating Unit**:

  If a WSN is designed to operate for a relatively long time, sensor nodes should be either equipped with balky batteries to guarantee the activity of sensor nodes or exploit power generating/harvesting modules [SAHP09] [Sto09]. The first solution only suits to the static application, although huge batteries cause lots of practical problems. However, in the case of mobility, the second solution should be considered. For instance, in [ZSLM04] a habitat monitoring network called ZebraNet is introduced in which sensor nodes are attached to the Zebras' body for tracking and studying their activities. The solution to provide the required power level at the sensor nodes is power harvesting. Solar cells are used in this project to provide the energy for the sensor nodes. Depending on the available resources, different power harvesting methods can be exploited in sensor nodes, some of which are reviewed in [SD09], [VSVH10] and [CC06]. Solar energy [ZSLM04], electromagnetic radiation [KVT09] and vibration [Lee07] are the widely used energy resources for harvesting.

2.1.2 Network Topology

WSNs are mostly in one of the two major forms of flat or clustered.

2.1.2.1 Flat

In this topology, the entire sensor nodes have the same role in terms of sensing and data communication or participating in the communication of the data of other nodes. Therefore, the deployment of flat WSNs is simple as sensor nodes are deployed without any priority.

2.1.2.2 Clustered

In clustered networks [SG04] [dCSI07], sensor nodes are grouped into clusters. In each cluster, a cluster-head is responsible to communicate with the head of the other clusters or with the destination. In data-centric networks, cluster-heads aggregate the data of their corresponding sensor nodes and relay them to the destination. Cluster-heads have usually similar capabilities as the other nodes, therefore nodes of each group take this responsibility in turn to regulate the energy consumption. In [PK05], an optimum cluster design model for WSN application is derived.

2.1.3 Data Communication Techniques

Data communication in data-centric WSNs is extensively discussed in [PKC10], [ZMW$^+$08] and [HP06]. In these networks, the entire sensor nodes act as sources generating data and trying to deliver the data to the destination. Data can be aggregated either on demand (Destination asks the sensor nodes to send their data), periodically or event-oriented (Sensor nodes send their data only if it includes new information). However, sensor nodes can apply various data communication techniques to send their data. The appropriate one is selected based on parameters such as the application area, network topology and dimensions, and sensor nodes' capabilities. In the following, some of the mostly used data communication techniques are reviewed:

2.1.3.1 Direct Communication

The simplest data aggregating method is direct communication between the destination and sensor nodes. As seen in figure 2.2, the Base Station (BS) as the destination broadcasts commands to handle the data aggregation procedure. The entire sensor nodes are in the coverage area of the destination and can individually communicate with the destination.

This method does not require complex processing within the sensor nodes. However, the size of the WSN in terms of the area it is deployed in is highly limited by the transmission range of the sensor nodes. The maximum area is a disk around the destination, with the radius equal to the transmission range of the senor nodes. In the case of resource-restricted sensor nodes with limited transmission range, this method only matches to small-sized WSNs. Other limiting factors of this method are the available spectrum and processing capability of the destination.

2.1.3.2 Hierarchical Communication

This approach is applied to clustered networks. Cluster-heads act as intermediate nodes. They aggregate the data of sensor nodes in their clusters and send them to the destination. This approach has the benefit that with

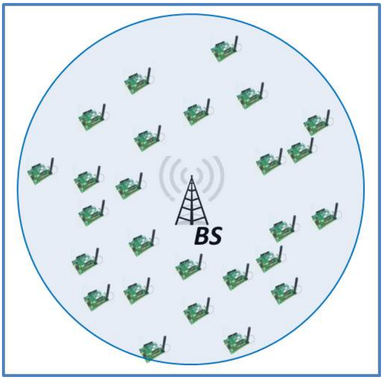


Figure 2.2: Direct data communication between sensor nodes and destination

little modification it can be integrated into the multi-hop technique. However, the capacity of a network that follows this data communication strategy is relatively low [GK00], [GV02]. Figure 2.3 shows the data communication procedure in cluster-based networks. This technique is applicable to more extended WSNs compared to the *direct communication* technique. However its scalability is still low.

2.1.3.3 Multi-Hop Communication

Figure 2.4 represents multi-hop (MH) data communication in WSNs. This method is applied to the networks with a flat topology. Thus, the entire sensor nodes have the same importance and can potentially take the same roles in data communication. MH is applicable even to extended networks in which *direct connection* or *hierarchical* methods are not feasible or exhibit low performance. According to MH, sensor nodes between source and destination relay messages and deliver them to the destination. The key enabling part of MH data communication is the routing protocols. They determine how to discover and maintain paths between sensor nodes and destination. Routing in WSNs will be discussed later in this chapter.

2.1.3.4 Mobile WSNs (MWSN)

In MWSNs [MBW+08] [WSC05], there are two kinds of nodes: sensor nodes which sense and generate data, and mobile nodes which move among the sensor nodes following a pre-defined or random manner, collect the data of

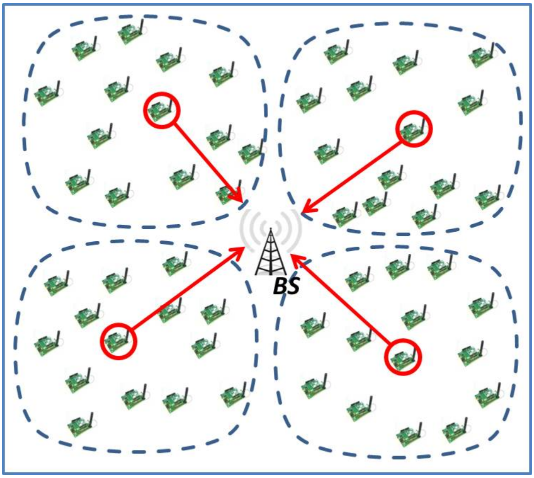


Figure 2.3: Hierarchical data communication in cluster-based WSNs

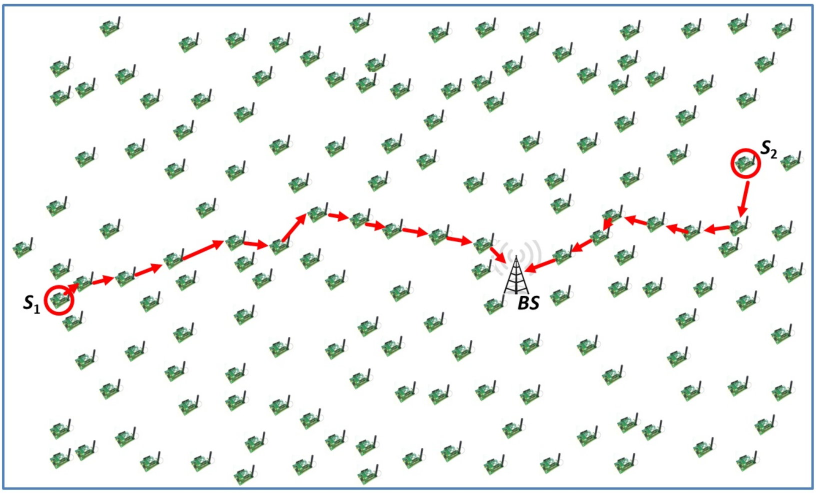


Figure 2.4: Data communication in multi-hop WSNs

sensor nodes and deliver them to a destination. For this, at each position, mobile nodes are accessible to a group of sensor nodes. Those sensor nodes that obtain data send them to the available mobile nodes. Depending on the mobility pattern of the mobile nodes, sensor nodes might have to wait and buffer their data. Therefore, in these networks latency is a critical factor.

2.2 Collaborative Communication (CC) in WSN

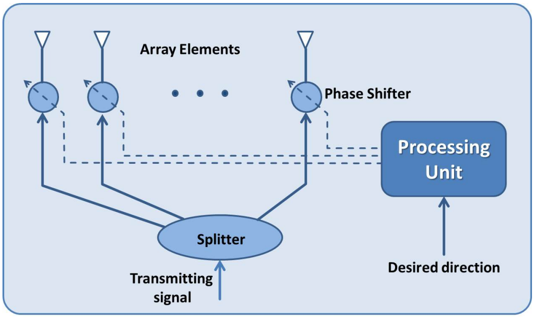
CC was originally proposed in transmit mode (CC-T) in [MHMB10]. It was also investigated from different aspects as distributed beamforming in [OMPT05], [MBMP09], [MHMB05], [AV08], collaborative transmission in [SB08b], [SB08a], and constructive interference [TP02], [TS10]. Especially in [OMPT05], [MBMP09], [MHMB05], CC-T is highly inspired by the standard array processing techniques such as beamforming. Therefore, in the next section, the beamforming theory is introduced.

2.2.1 Beamforming

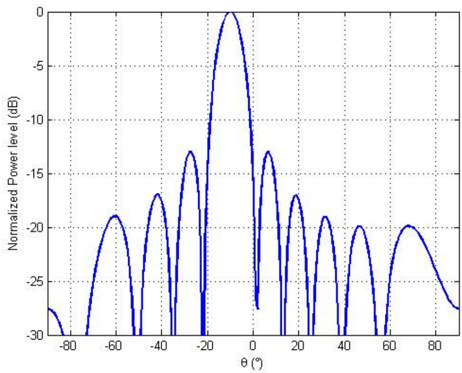
In beamforming systems [Tre02], an array of omni-directional sensors (antennas in the case of RF applications) is applied to form a specific kind of beam-pattern. Beamforming has different applications in data communication. In the case of data transmission, the entire elements of the array are fed by the same signal. Then, as seen in figure 2.5(a), in each element the phase shifters change the carrier phase of the signal before transmission by the antenna. Depending on the phase shifts and the paths the signals of the array elements pass through, the combination of the multiple signals might be either destructive or constructive in specific points around the array. Figure 2.5(b) illustrates the resulting beam-pattern when a Uniform Linear Array with 10 elements is applied. The array is set to steer a directive beam towards -10.

2.2.2 Collaborative Communication for Transmit Mode (CC-T)

Similar to beamforming, the major goal of CC-T is to extend the transmission range of resource-restricted sensor nodes in a certain direction. According to CC-T, a group of sensor nodes, called *C-nodes*, collaborate to simultaneously send a common signal to a specific destination. This scenario is illustrated in figure 2.6. The destination receives the combination of the multiple signals. The overall quality of the received signal highly depends on the phase and frequency of the C-nodes' carriers. In other words, if C-nodes modify their



(a) Standard beamforming



(b) Corresponding beam-pattern to a Uniform Linier Array of 10 antennas

Figure 2.5: A view of the standard beamforming systems

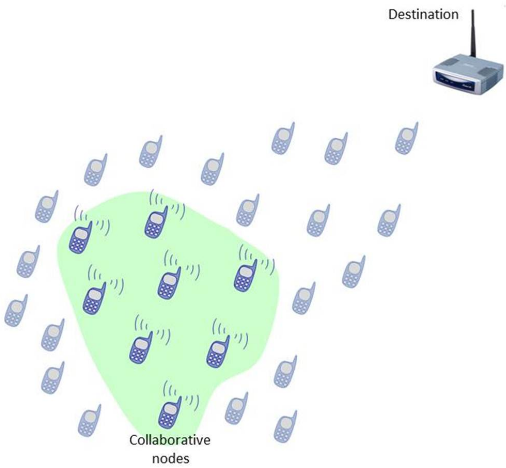


Figure 2.6: Illustration of the arrangement of C-nodes and destination in CC

carrier's phases and frequencies, the destination would receive a constructive combination of their signals and in comparison to the power level of the individual C-nodes, higher power level is attained. This improvement can be applied either to extend the transmission range or to enhance the signal quality at the destination.

Although CC-T and transmit beamforming follow a same basis, there are essential differences between these two techniques. In comparison to the standard beamforming, in CC-T:

- Sensor nodes have random and unknown locations
- There is no reference angle
- The direction of the target is not available
- The phase and frequency of C-nodes are different

These differences make CC-T a more elaborate approach than beamforming and affect the way CC-T generates the beam-pattern. Since the direction of the target and position of the C-nodes are not known in advance, C-nodes modify their carrier phases based on the interactions with the destination so that the power level of the signal received by the destination improves.

The feasibility of CC-T has been shown in theory as well as in laboratory settings using software radio [SB08b] [BGS$^+$11], but also in practice using commercial off-the-shelf (COTS) hardware (e.g. [KBW04]). CC-T is able to extend the transmission range in a communication link [SB08b], increase signal power and quality at the destination [AV08] and reduce the interference level due to the destructive combination of the multiple signals in directions other than the destination's direction [MHMB10].

In CC-T, *synchronization* is defined as the appropriate phase and frequency modifications during interaction between C-nodes and destination based on which signals of the C-nodes are constructively combined at the destination. Synchronization is performed in terms of frequency and phase.

2.2.3 Frequency Synchronization for CC-T

In WSNs, sensor nodes have independent local oscillators (LO). The desired frequency is generated by multiplying the frequency of a crystal oscillator by a fixed nominal frequency. In this method, differences among different carrier frequencies are in the range of $10 - 100$ parts per million (ppm) with respect to the nominal [MHMB10]. The carrier signal of each sensor node is [PS07]:

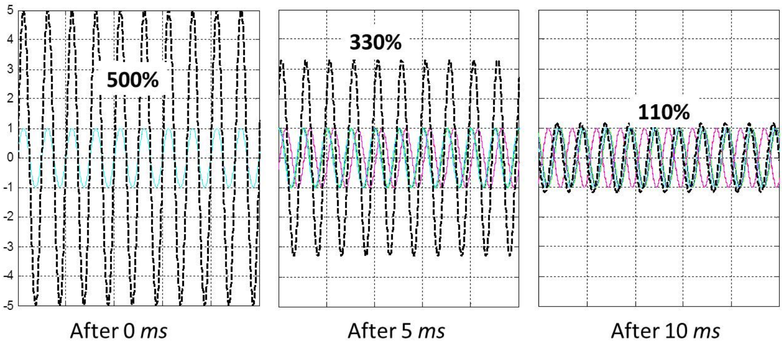
$$S_i(t) = A_i e^{j(2\pi(f_c + f_{err})t + \phi_{err})} \tag{2.1}$$

where

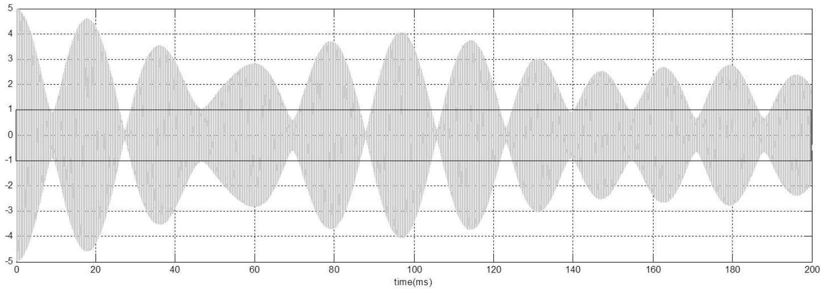
A_i	Amplitude
j	Imaginary operator $\sqrt{-1}$
f_c	Nominal frequency
f_{err}	Frequency error at i-th node
ϕ_{err}	Phase error at i-th node

Since frequency is multiplied by time, the negative effect of frequency error (f_{err}) varies over time. This effect is represented in figure 2.7. In this figure, the entire C-nodes have sinusoidal signals with nominal frequency of 1 MHz and normalized amplitude. It is assumed that the signals are co-phase, i.e. there is no phase error in the signals combined at the destination. However, they have random frequency errors in the range of $10 - 100$ Hz. Figure 2.7(a) represents three snapshots of the signals of 5 C-nodes (solid colored signals) and the collaboration result (dashed black signal) for each. Snapshots are in the length of $10\mu s$ and respectively correspond to 0, 5 and 10 ms. Frequency errors of the C-nodes in this analysis are respectively $+41, -12, +38, -13, +49$ Hz.

The major impact of frequency error on the collaboration is on the amplitude. At the beginning, the frequency errors are negligible and the highest possible



(a) Different snapshots of C-nodes and CC-T output



(b) The envelop of the CC-T output in the case of frequency error

Figure 2.7: Impact of frequency error on the performance of CC-T

efficiency (400% improvement in the amplitude) is achieved. However, after 5 ms, instead of 400% increase, the amplitude of the received signal at the destination only increases 230%. The negative effect of errors increases even more so that after 10 *ms*, there is only 10% improvement. Frequency error deviate the signal shape as well. But due to the low level of errors (less than 1%), this effect is not so problematic. Figure 2.7(b) shows the envelope of the CC-T output in the presence of frequency errors in a relatively wide range. It shows that the impact of frequency error is not periodic and it might lead to receiving a lower signal quality in comparison to the signal quality of the individual C-nodes.

One widely used frequency synchronization approach is based on *Master-Slave* interaction of C-nodes with the destination [TP02] [BIVP08]. The destination as a *Master* broadcasts a pilot signal called *beacon*. C-nodes as *Slaves* use their phased locked loops to lock to the reference frequency and remove their errors. If the beacon is long enough, C-nodes are able to compensate their frequency error. Depending on the stability of the local oscillators at C-nodes and destination, this process might be repeated in certain periods to correct C-nodes' carrier frequencies.

This analysis is independent of the amplitude of the C-nodes' signals. In addition, frequency error relates to the nominal frequency. Therefore, the results are valid for each sinusoidal signal with different amplitude or frequency. However, the envelop of the CC-T output is extended or compressed by the variation of the nominal frequency.

2.2.4 Phase Synchronization in CC-T

After the compensation of the frequency error, C-nodes should be synchronized in terms of their carrier phases. Phase synchronization in CC-T refers to modifying the carrier phase of the C-nodes so that the destination constructively receives their signals. Without appropriate phase synchronization, CC-T might even have negative effect on the signal quality at the destination. This effect is illustrated in figure 2.8. In this figure, the same scenario as that of figure 2.7 is used. The only difference is that in this case, there is no frequency error, but the signal of each C-node has a random carrier phase in the range of $(0 \quad 2\pi)$. The three snapshots are identical in terms of the amplitude of the CC-T output. It shows that phase error has a constant impact over time. Furthermore, phase errors of C-nodes are location-dependent: The phase error of a specific C-node at the destination is $\phi_{err} = \phi_0 + \phi_l$ where ϕ_0 is its initial phase offset and ϕ_l is phase shift due to its distance to the destination. It is calculated as:

$$\phi_l = \frac{2\pi \cdot l}{\lambda} = \frac{2\pi f_c l}{C} \tag{2.2}$$

where

l	Distance between C-node and destination
λ	Wavelength of the C-node's carrier
f_c	Carrier frequency of the C-node
C	Wave propagation speed

Therefore phase synchronization of C-nodes is much more challenging compared to the frequency synchronization, especially in the case of mobility which ϕ_l continuously changes. Since ϕ_l directly depends on f_c, in the case

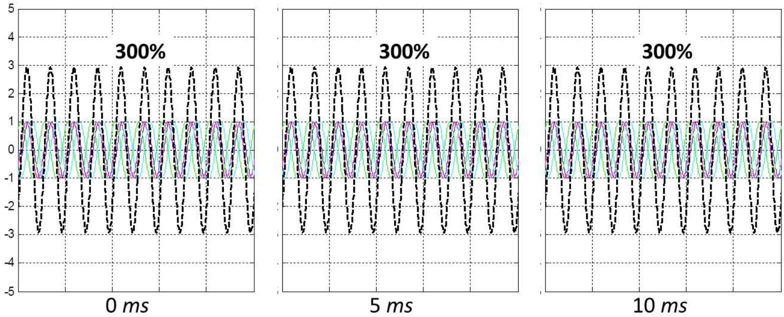


Figure 2.8: Impact of phase error on the performance of CC-T

of higher frequencies this problem would be more critical and even small movements of the C-nodes result in significant changes in ϕ_l.

The problem of phase synchronization in CC-T raises because of either the different initial phase offsets of C-nodes or unequal distances between C-nodes and destination (ϕ_0 or ϕ_l in equation 2.2, respectively). But now the question is how can C-nodes estimate their phase errors in order to compensate them? Various methods for synchronization of C-nodes have been presented in the literature. They can be classified into the following approaches:

- **Iterative/Non-Iterative**: In non-iterative methods, the destination estimates appropriate phase shifts based on some limited interactions with C-nodes and sends the estimation results to them. In iterative methods, on the other hand, synchronization is a continuous process and at each iteration, the signals of C-nodes become more synchronized. Iterations are continued until the desired synchronization level is achieved.
- **Closed-/Open-Loop**: The *loop* here refers to the connection between C-nodes and destination. In closed-loop synchronization, destination is the coordinator of synchronizations, i.e. it is in direct contact to the C-nodes. But Open-loop methods are based on the minimum interaction of the C-nodes with destination. The major part of synchronization is performed through interactions among C-nodes.

In the following, we introduce some of the mostly used synchronization methods in CC-T. In all of these methods, it is assumed that C-nodes are firstly synchronized in terms of their carrier frequency.

Table 2.1: Different steps of full-feedback closed-loop synchronization method

Destination	Broadcasts a *Synch.* message through C-nodes.
C-nodes	Receive and send *Synch.* back the message
Destination	Receives and extracts the signals of C-nodes
Destination	Estimates the phase of each received signal
Destination	Calculates the appropriate phase shifts for each C-node
Destination	Sends the phase compensation data to C-nodes
C-nodes	Receive and apply the phase shifts to the carrier signals

2.2.4.1 Full-Feedback Closed-Loop

This method is originally proposed by Tu, et.al [TP02] as one of the first synchronization approaches and widely used in CC-T by Mudumbei [MHMB10], [MBMP09], Banitalebi [BSB10b], [BGS$^+$11], and many other researchers. It is a closed-loop and non-iterative method and is detailed in table 2.1.

This method is very simple and robust. So it is applicable for a large variety of WSNs. But it has the following drawbacks:

- It is based on the assumption of the same performance of C-nodes when they receive and send back the *Synch.* message to the destination. But this assumption is not true in all scenarios. Sensor nodes might have different tasks due to their especial position or sensor types. To handle multiple tasks, C-nodes might share their resources which would result in different time delays when they receive and send the *Synch.* message back.
- The available spectrum is not efficiently used. The entire C-nodes need separate channels to individually contact the destination. It decreases the scalability of this synchronization method, i.e. this method is applicable only for limited number of C-nodes.
- The accuracy of this method highly depends on the processing capability of the destination.
- The processing load is unbalanced: the most steps are performed by destination. It decreases the scalability as destination can support limited number of C-nodes.

2.2.4.2 Time-Slotted Round-Trip Carrier Synchronization

This synchronization method is originally introduced in [BIVP08] and discussed further in [OBI07]. The key feature of Time-Slotted Round-Trip Car-

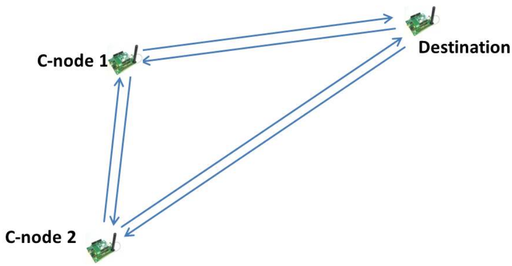


Figure 2.9: Round-trip synchronization approach

rier Synchronization is that it is open-loop and its processing load is distributed so that the entire nodes including C-nodes and destination have the same role and importance in synchronization.

The idea behind this scheme is the equivalent round-trip propagation phase shift through a multi-hop path, including C-nodes and destination. This is why this scheme is called the round-trip carrier synchronization. Based on the arrangement and the number of C-nodes, a loop including the entire C-nodes and destination is designed. As a simple case, the operation of round-trip scheme for synchronization of the two C-nodes is represented in figure 2.9. First a loop including the entire C-nodes and destination is considered. The destination sends a *Synch.* message round the loop both in clockwise and counterclockwise directions. These messages travel through the loop and are finally received by the destination again. Provided that the channels which are used during multi-hop connections are reciprocal, the two received messages will have the same overall phase shifts and therefore the messages are synchronized. A more complex scenario including more than two C-nodes is analyzed and discussed in [BIVP08].

If C-nodes relay the *Synch.* messages one hop per time slot, the total time of synchronization is equal to $2N - 1$ time slots, where N is the number of C-nodes. The major problem associated with the round-trip synchronization technique is that its complexity considerably increases with increasing the number of C-nodes considering the complexity of designing appropriate loops to compensate the phase errors.

2.2.4.3 One-Bit Feedback Closed-Loop (OBCL)

This synchronization method is first introduced in [MBMP09] [MHMB05]. The major idea behind this approach is to have a simple synchronization method similar to full-feedback closed-loop, but easily scalable and less resource-demanding. One-Bit Feedback Closed-Loop (OBCL) is an iterative

Table 2.2: Steps of OBCL synchronization approach

First iteration ($i = 1$):	
C-nodes	Adjust their carrier phases randomly.
C-nodes	Send a *Synch.* message simultaneously over the same channel.
Destination	Estimates the SNR of the received signal and consider it as the reference level (SNR_0).
Later iterations ($i > 1$):	
C-nodes	Modify their carrier phase randomly.
C-nodes	Send a *Synch.* message simultaneously over the same channel.
Destination	Estimates the SNR of the received signal (SNR_i).
Destination	Compares SNR_i with SNR_{i-1}.
	If ($SNR_i > SNR_{i-1}$):
Destination	Sends a one-bit positive feedback.
C-nodes	Keep their recent phase modifications.
Destination	Considers SNR_i as the new reference level.
	Else
Destination	Sends a one-bit negative feedback
C-nodes	Cancel their recent phase modifications.

synchronization approach which is implemented as follows:

At each iteration, C-nodes utilize the same channel for simultaneously sending of a *Synch.* message to the destination. Destination receives the message and estimates the overall SNR. In the first iteration it is considered as a reference SNR. In the following iterations, however, the destination compares this SNR with the reference level and sends a one-bit feedback representing the comparison results to the C-nodes. In addition, it renews the reference level if higher SNR is achieved. C-nodes keep their recent phase modifications if they had positive effect on the overall SNR, otherwise they cancel the phase modifications.

Although carrier phases randomly change during OBCL, they finally converge to their optimum values. The reason is that only those of the random phase shifts that have positive effect on the output SNR are maintained. But due to the random variation of the carrier phases, the number of iterations to gain a certain synchronization level would be also a random parameter. In [MHMB05], it is proved based on the numerical analysis that 75% of the amplitude which is achievable in the case of ideal synchronization is achieved in roughly $5N$ iterations on average, where N is the number of C-nodes. In addition, in [MHMB10] it is shown that perfect phase coherency with probability equal to one using OBCL is in principle achievable.

Although at each iteration the synchronization of the C-nodes statistically improves, in practice it is necessary to define a limit for the iterations. One limit can be a fixed number of iterations or equivalently a fixed amount of energy consumption regardless of the synchronization accuracy. Another limit would be a certain synchronization level. The number of iterations to satisfy this limit would be a random variable.

OBCL has the following positive characteristics:

- C-nodes do not need individual sub-channels to contact the destination
- Processing load at destination is much less than in full-feedback closed-loop case (just the calculation of SNR and sending of one-bit feedback).
- OBCL is iterative, thus different levels of synchronization just by controlling the number of iterations is achievable.
- The work load of C-nodes and destination is independent of the number of C-nodes.
- Unlike full-feedback closed-loop method, the accuracy of OBCL is not limited by the processing capabilities of the destination.

However, similar to full-feedback closed-loop method, in OBCL C-nodes and destination should be in the coverage area of each other. The destination directly sends feedbacks to the C-nodes. In addition, at the beginning of synchronization the combination of the C-nodes' signals at the destination is not constructive. Therefore there is not necessarily an extension in the transmission rage and the destination should be in the coverage area of C-nodes.

Since in OBCL method the number of iterations to gain a specific level of synchronization accuracy is random, it is difficult to calculate the energy efficiency of this method.

2.2.4.4 (1+1)-Evolutionary Algorithm

This synchronization approach was originally proposed by Sigg et.al [SB08b] [SB08a]. Similar to OBCL, (1+1)-Evolutionary Algorithm ((1+1)EA) is iterative and fully based on the short (one-bit) feedbacks of the destination. But it is able to synchronize carriers of the C-nodes in terms of both frequency and phase. In addition, (1+1)-EA suggests different approaches to modify the phase and frequency of the C-nodes.

(1+1)-EA considers the synchronization scenario as an optimization problem.

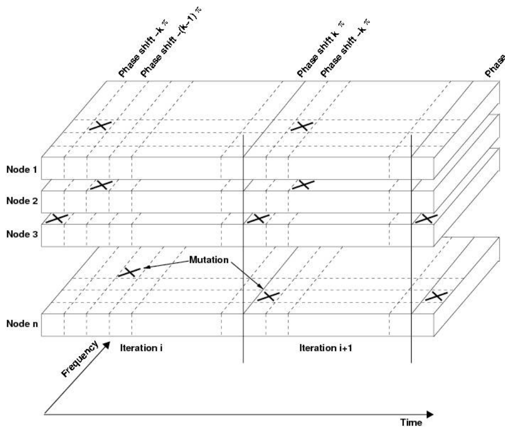


Figure 2.10: Search space of (1+1)-EA synchronization approach [SB08b]

As seen in figure 2.10, the search space is characterized by the combined frequency and phase shifts. Each point in the search space refers to one configuration of transmitted signals. At each iteration a random set of C-nodes are deactivated and active C-nodes act similar to OBCL approach: they select random sets of phase and frequency shifts and send a *Synch.* message. The destination finds out if the new set has positive effect or not. In the case of positive effect, changes are kept otherwise they are canceled.

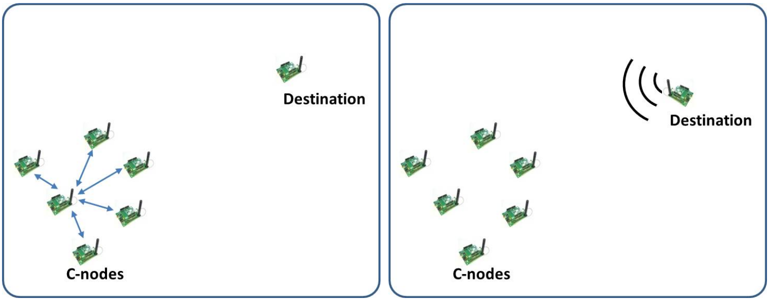
In comparison to OBCL, (1+1)EA randomly deactivates some of the C-nodes at each iteration. Unfortunately, there is no comparison to see the impact of C-nodes' deactivation on the synchronization performance. In addition, (1+1)EA synchronizes C-nodes in terms of both phase and frequency whereas the focus of OBCL is only on phase synchronization.

2.2.4.5 Master-slave open-loop

Master-slave open-loop synchronization approach [TP02], is highly inspired by master-slave frequency synchronization technique. The differences between these two approaches are due to the different characteristics of frequency and phase. Frequency is an absolute value and is measured without needing a reference but phase is a relative quantity and is measured relative to a reference value. In addition, contrary to the frequency, the phase of a signal depends on the path through which the signal travels. Thus, it is impossible for C-nodes to modify their carrier phases based on the *Synch.* message which they receive from the destination. Open-loop master-slave

Table 2.3: Summarization of (1+1)-EA synchronization approach

First iteration ($i = 1$):	
C-nodes	Adjust their carrier phases and frequency randomly.
C-nodes	Send a *Synch.* message simultaneously over the same channel.
Destination	Estimates the SNR of the received signal and considers it as a reference level (SNR_0).
Later iterations ($i > 1$):	
C-nodes	Decide randomly if they remain active in this iteration or not.
Active C-nodes	Modify their carrier phase and frequency randomly.
Active C-nodes	Send a *Synch.* message simultaneously over the same channel.
Destination	Estimates the SNR of the received signal (SNR_i).
Destination	Compares SNR_i with SNR_{i-1}.
	If ($SNR_i > SNR_{i-1}$):
Destination	Sends a one-bit positive feedback.
Active C-nodes	Keep their recent phase and frequency modifications.
Destination	Updates its reference level with SNR_i
	Else
Destination	Sends a one-bit negative feedback
Active C-nodes	Cancel their recent phase and frequency modifications.



(a) Full-feedback Closed-loop phase synchronization (interactions are among C-nodes)

(b) Open-loop compensation of the phase errors due to different position of the C-nodes

Figure 2.11: Master-slave phase synchronization

phase synchronization is realized in two steps:

- **Step 1**: Synchronization of the entire C-nodes regardless of the position and carrier phase of the destination
- **Step 2**: Modification of the carrier phase of C-nodes so that their signals are synchronously received by the destination

In step 1, the procedure to unify carrier phases of C-nodes is almost the same as full-feedback closed-loop approach. The difference is that in Master-Slave approach, one of the C-nodes coordinates the synchronization. For this, the coordinator broadcasts a *Synch.* message to the other C-nodes. They receive it and send it back to the coordinator. The coordinator estimates appropriate phase shifts for each C-node and sends the phase compensation information back. Now, the entire C-nodes have the same phase, however due to their random distance to the destination, they are not ready for CC-T.

In step 2, the destination broadcasts a *Synch.* message to the C-nodes. Since the C-nodes have already been synchronized (have the same carrier phases), each C-node uses its own signal as a reference to detect the phase shift due to its distance to the destination. After compensation of this part of the phase error, signals of the C-nodes are synchronized at the destination. Figure 2.11 shows haw this method works.

2.3 Routing in WSNs

Routing protocols are the key enabling part of multi-hop networks as they discover and maintain paths among the sensor nodes to the destination(s).

Most of them are originally designed for wired networks and later are applied to wireless applications as well. However due to the differences in these two kinds of networks, they are modified to match to wireless networks.

2.3.1 Methods of Categorizing the Routing Protocols

Routing protocols can be classified in different terms [AKK04] [AY05]:

- **Distance-Vector or Link-State:** Distance vector protocols calculate their distance to a certain destination from the entire potential paths and select the best one whereas link state protocols track the status of each link and apply a metric to evaluate the cost of the links and select the optimum path to the destination.
- **Flat or Hierarchical:** In flat networks, the entire nodes have the same role and priority for routing. But in hierarchical networks, a layered topology is considered. Sensor nodes in lower layers cannot directly connect to each other. For communication, they connect to their corresponding nodes in higher layer. Each node relays both its own packets and packets which are received from its corresponding nodes in lower layer.
- **Proactive or Reactive:** In proactive approaches the entire possible routes in the network are discovered in advance and are periodically updated depending on the dynamic situation. In reactive routing, however, routes are discovered on demand. Proactive routing is relatively fast but it is also resource demanding with low scalability. In comparison, reactive protocols are resource efficient and scalable even to very large networks, but relatively slow due to their on-demand route discovery.
- **Available Location Information:** Three levels of location information can be defined for sensor nodes:
  - Totally blind in terms of their own position, neighbors and direction of destination
  - Aware of the list of neighbors
  - Aware of their absolute position

2.3.2 Appropriate Routing Objectives to be Applied in WSNs Applications

As a special kind of wireless networks, WSNs can use most of the existing routing protocols which are proposed for wireless networks. But WSNs are application-specific networks with battery-based resource restricted nodes that might also have high mobility. Therefore, some of the existing protocols do not perfectly match to WSNs.

The major factors which influence the routing protocol design in WSNs are listed below. These terms can be mentioned as the main WSN's objectives.

- **Energy Efficiency:** In most of the WSNs, sensor nodes are powered by limited energy sources (batteries) which usually are not rechargeable or replaceable. Thus the lifetime of the network highly depends on the operation of the nodes. Sensor nodes have three major tasks: sensing, processing and data communication. Data communication including interaction with the other nodes for route discovery as well as sending or relaying of data messages is almost the most energy consuming task of sensor nodes in multi-hop networks [SCI$^+$01]. Although the structure of the sensor nodes especially in terms of RF and antenna plays a key role in the amount of energy consumed to send or receive a certain message, routing protocols deeply affect the energy efficiency. An efficient routing protocol selects the path with the lowest cost to deliver a certain message.
- **Reliability:** In most WSN applications, compared to their surrounding objects sensor nodes are relatively small, therefore they can be easily blocked. In addition, sensor nodes have usually short transmission range and even small movements might disconnect them from their neighbors. These reasons result in an inherent low reliability in WSNs which negatively affects the quality of data communication. It can be partially compensated using channel coding as well as diversity. However, this problem can also be considered in routing approaches. More specifically, sensor nodes with higher stability can be selected as relay nodes to increase the overall reliability.
- **Cost Efficiency:** As mentioned in chapter 1, the WSNs that we focus on in this thesis are composed of quite simple sensor nodes with limited capabilities in terms of sensing, memory and processing, RF and data communication, and battery storage. Routing algorithms which are suggested for such networks should be relatively simple still efficient. Sensor nodes are not able to keep large routing tables or carry out complex processing to find the optimum route to the destination.
- **Scalability:** The number of sensor nodes in a WSN might range from

hundreds to thousands and even millions of nodes. On the other hand, due to the dynamic situation, the number of active nodes in a particular area might be variable. Routing protocols should maintain their quality for different size of the network.

- **Autonomous Activity:** After being deployed, physical access to the sensor nodes is usually impossible. On the other hand, WSNs have usually dynamic situations. Therefore, matching the routing protocol features to the current network state (topology, objectives, etc.) is not feasible. Sensor nodes should be able to autonomously match their activity based on the current situation of the network.

2.3.3 State of the Art of Routing Protocols in WSNs

Routing protocols in WSNs are thoroughly reviewed in [AY05], [AKK04]. In this section we review some of the widely used routing protocols.

2.3.3.1 Flooding and Gossiping

Flooding and Gossiping are the simplest forms of routing. They have been first proposed by Hedetniemi in [HL88] and improved in [LMM99] and [YCY08] as reliable data communication approaches for small networks.

According to flooding, the source node sends its data all around the neighbors. The neighbors relay messages to all of their neighbors which have not received the message yet. This process is continued until the message is delivered to the destination. But data communication process in not stopped at this stage because the message delivery is not announced to the other nodes. Therefore the data communication process is continued until the entire nodes receive the message. Gossiping is based on flooding, but each node relays the message to one of its neighbors which is randomly selected. The idea behind gossiping is to increase energy efficiency. Obviously gossiping is slower than flooding.

The main advantage of these two protocols is their simplicity. In addition, sensor nodes do not need to maintain routing information. However, they have the following drawbacks:

- **Energy inefficiency:** In flooding, independent of the distance between source and destination, transferred messages are communicated to the entire nodes.

- **Low scalability:** Data communication costs to communicate a message between a specific pair of source and destination is independent of their position because the message reaches the entire nodes of the network. Therefore these methods do not match to relatively large networks.

- **Memory-less Routing:** Considering a specific source and destination, data communication for the second time would have more or less the same cost as the first time.
- **High Latency:** When gossiping is applied, data communication process may suffer from high delays even if the source and destination are in the same vicinity.
- **Implosion:** A certain node might receive the same message from multiple neighbors.

2.3.3.2 Sensor Protocols for Information via Negotiation

Sensor Protocols for Information via Negotiation (SPIN) [KHB02] is rather similar to flooding but due to the application of negotiation, it solves the problems of classic flooding and gossiping. According to this protocol, sensor nodes name their data using high-level data descriptors, called meta-data. Meta-data is used during negotiations to eliminate the transmission of redundant data throughout the network. In addition, according to SPIN, sensor nodes can base their communication decisions both upon application-specific knowledge of the data and upon knowledge of the resources that are available to them. Assuming a limited energy supply, this allows the sensor nodes to efficiently distribute data.

SPIN is simulated and compared to flooding and gossiping in [RKB99]. It is shown that in a relatively small network (25 nodes) and under overall energy constraint, SPIN has a 60% higher performance in terms of the number of delivered messages.

2.3.3.3 Directed Diffusion

Route discovery in Directed Diffusion [IGE00] [VOCA09] [IGE$^+$03] begins from the sink and is composed of the following two steps:

- **Query Propagation:** The sink generates a request message called *interest* which is specified according to the attribute-value of the target data message and periodically broadcasts it to the entire network by flooding. Interests are cached by neighbors and *Gradients* are set up pointing back to where interests came from at a low data rate. It automatically establishes multiple paths for each potential source which during *reinforcing* of one or a small number of paths with the minimum cost have been selected.

- **Data Propagation:** sensor nodes search in their interest cache for matching interest entry. They forward the data according to the gradients associated to the interest. The receiver node finds matching entry in interest cache and forwards it again according to its interest cache. If there is no matching entry, it drops the message.

2.3.3.4 Low Energy Adaptive Clustering Hierarchy

Low Energy Adaptive Clustering Hierarchy (LEACH) [HCB00], [Gan02] is a hierarchical cluster-based routing protocol. Sensor nodes are classified in two different layers: cluster heads and cluster members.

Cluster heads are responsible for periodically aggregating and compressing the data of their cluster. LEACH uses a Time/Code-Division Multiple Access (TDMA/CDMA) MAC technique to reduce inter-cluster interference [HZB10]. This protocol is highly appropriate for the applications in which a continuous monitoring is on demand. Cluster heads are in direct contact to the destination (Sink) to deliver the sensing data by the members of their corresponding clusters. In order to equalize energy consumption, the cluster head is periodically changed.

Although LEACH is able to increase the network lifetime, there are still a number of issues about the assumptions used in this protocol. LEACH assumes that all nodes can directly contact the destination and have adequate computational power to support different MAC protocols. Therefore, it is not applicable to networks deployed in large regions. It also assumes that nodes always have data to send, and those located close to each other have correlated data.

The assumption of constant data transmission decreases the energy efficiency of data communication which is a critical issue in WSNs. In order to solve this problem Ali et.al in [ADB08] has proposed an improved version of LEACH called Advanced LEACH (ALEACH). It suggests an autonomous way to arrange cluster members based on their available energy resources. One with higher energy storage level is selected as the cluster head. In [AYK10] another version of LEACH is introduced in which clustering process is performed cooperatively during a virtual Multi-Input Multi-Output (MIMO) approach.

2.3.3.5 Geographic Adaptive Fidelity

Geographic Adaptive Fidelity (GAF) [XHE01] is an energy-aware location-based routing algorithm. It increases the energy efficiency by turning off those nodes which have no role in a certain data communication. According to GAF, each node is aware of its location. The entire nodes are partitioned into grid squares, where any two nodes in adjacent grid squares are within the range of each other. At any given time, only one node in each grid square needs to be activated to handle the routing tasks. For communication of a message, at each time only the active nodes of five grids including one holding the transferred message and the four adjacent ones are engaged. In addition, in order to avoid early exhaustion of the active nodes, this task is periodically cycled.

GAF strives to keep the network connected as in [SK00], [RM99], by keeping a representative node always in active mode for each region on its virtual grid. Simulation results show that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency and packet loss and increases the lifetime of the network by saving energy. Although GAF is a location-based protocol, it may also be considered as a hierarchical protocol where the clusters are based on geographic location. For each particular grid area, a representative node acts as the leader to transmit the data to other nodes. The leader node however, does not perform any aggregation or fusion as in the case of hierarchical protocols [RP10].

2.4 Mobile Wireless Sensor Networking

The application of mobile nodes for data aggregation is widely reviewed in [MBW+08] [WSC05] as Mobile Wireless Sensor Networking (MWSN), or in [SH07] [YX10] as Delay Tolerant networking approach or Opportunistic Routing [PMM07].

MWSN is an efficient networking approach which suits the resource-restricted sensor nodes. A MWSN is composed of the two sets of elements:

- **Sensor Nodes:** These nodes are usually static and sense specific factors and generate data
- **Mobile Nodes:** These elements of the network move among the sensor nodes and enhance the data aggregation performance

Despite of the MH based WSNs in which a considerable amount of sensor nodes' resources is spent for networking and data communication, in MWSNs sensor nodes only sense and prepare data to send to the base station. Mobile nodes, on the other hand, can improve the networking performance in different ways. One type of the application of mobile nodes for networking which is considered in this thesis is data aggregation from the sensor nodes. They move among the sensor nodes and at each time those sensor nodes which are in the coverage area of the mobile nodes deliver their data. Therefore the mobility pattern and number of mobile nodes are the key factors to determine the network performance during data aggregation.

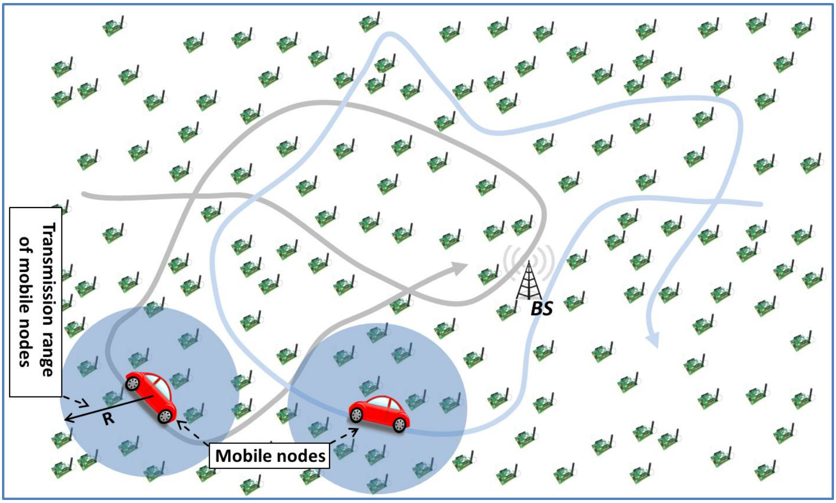


Figure 2.12: Data communication in mobile WSNs

A simple view of this technique is represented in figure 2.12. Mobile nodes move according to either pre-defined or random paths. They broadcast specific messages announcing their presence. At each time, those of the sensor nodes which are in the coverage area of a mobile node and receive its message, contact the mobile node and send their data. During their movement, when mobile nodes approach to the destination, they deliver the entire aggregated data.

In MWSN, sensor nodes have very simple tasks in terms of data communication and networking. In specific periods of time, they listen to the channel and as soon as they detect a mobile node, send their data. Moreover, despite MH networks sensor nodes do not participate in the data communication of the other nodes and efficiently save their energy. Therefore, this idea perfectly matches to the resource-restricted sensor nodes which have low processing capabilities and battery storage.

The cost paid for this high simplicity in the sensor nodes' activity would be the continuous movement of some mobile nodes inside the network. In addition, depending on the mobility pattern of the mobile nodes, sensor nodes should wait for a while to meet a mobile node and deliver their data. It is why these networks are also called delay tolerate networks. To design the mobility pattern of mobile nodes, the maximum tolerable delay should be considered because after this time, the data of the sensor nodes are not valid anymore.

2.5 Summary

In this chapter, a short introduction to WNSs and sensor nodes is given, followed by presenting the state of the art on the CC approach. CC is introduced as a general platform including initialization, synchronization and data communication steps. Among these steps, the synchronization step is the most challenging part and has absorbed great research efforts. Various synchronization approaches are reviewed which will be applied in the next chapter to select the one which is the most suitable to fulfilling the necessary features that the CC approach should have to be integrated with networking techniques.

Finally, different networking techniques in WSNs were introduced which are used in chapters 4 and 5 to develop MH-CC and CC-MWSN by the integration of CC into these networking approaches.

Chapter 3

Collaborative Communication (CC)

The goal of this chapter is to develop a suitable collaborative communication (CC) approach, dubbed CC+, which can be integrated to networking techniques. As the first step, appropriate features of CC+ are proposed. Then, based on the literature review in chapter 2, one of the existing CC approaches which has the potential to fulfill the desired features is selected. This forms the *basis* for further development. The comparison of basic CC and CC+ demonstrates the drawbacks of the basic CC which are then used to propose and implement appropriate ideas to achieve CC+.

CC+ is applied as the major data communication approach in extended WSNs in chapters 4 and 5. Therefore, even small changes in its performance could have significant effect on the overall performance of the WSN. Hence, the performance of CC+ as well as its implementation costs in terms of energy consumption is also discussed in detail.

3.1 Major Features of the Appropriate CC Approach

According to the major goal of this research, CC+ should definitely be highly reliable and flexible. Reliability is defined as the capability of maintaining the connection between source and destination even in the case of the failure or movement of some of the effective nodes in data communication. Based on this definition, the entire reviewed CC approaches have more or less good reliability as they are based on the communication of a specific message by a group of collaborative nodes (C-nodes).

Flexibility is also defined as the capability of modifying the data communication characteristics such as data delivery rate and energy efficiency without the need for restarting the data communication approach or the need for specific features in sensor nodes such as capability to change their individual transmission range by changing their transmission power level. Based on this definition, various synchronization approaches have different levels of flexibility.

In addition, there are other extra features which extend the application scenarios of CC+ and the networking approaches which are developed in the next chapters. Major expected features of CC+ are addressed in this section.

3.1.1 Flexibility

The flexibility of CC techniques refers to their capability to modify the transmission range by changing of either the number of C-nodes or the synchronization accuracy level. Therefore, non-iterative synchronization approaches have low flexibility because of their fixed accuracy level. In addition, in the case of joining new C-nodes, CC should be interrupted.

In terms of the speed of data communication and delivery rate, using the maximum number of C-nodes and synchronization accuracy to extend the transmission range is the optimum situation. However, as we will show later in this chapter, this setting would lead to low energy efficiency. Therefore, CC+ should be flexible to switch to different setting and follow the dynamic situation in an energy efficient way.

3.1.2 Energy Efficiency

The major cost of CC is in terms of energy consumption due to the increased intra-node interactions for setting up and synchronization of C-nodes. Energy efficiency is one of the hot topics in WSNs and is considered in the design and implementation of data communication and networking techniques. However, compared to the state of the art on energy efficient CC approaches, a higher level of energy efficiency is achievable. In this work, energy efficiency has higher priority due to the wide application of CC and its determinant role in the overall energy consumption and life-time of the network.

3.1.3 Distributed Structure

Central processing simplifies CC in terms of the interaction among nodes which regarding resource restriction of the nodes is a desired feature. However, as mentioned in chapter 2, it decreases the performance and scalability of CC. Distributed approaches, however, are more scalable and since resources of multiple nodes are shared, higher level of performance in terms of energy regulation is achievable. On the other hand, centralized approaches suit more applications in which special nodes with extra resources coordinate the collaboration. But in this work, the entire nodes including destination are the same and have limited resources. Therefore, distributed structure would be one of the main objectives of CC+. Another reason which supports the high importance of the distribution in the CC+ approach is the need for high level of scalability of CC.

3.1.4 Autonomous Activity

The dynamic situation of the sensor nodes and their surrounding objects result in continuous changing of the network topology. Therefore, setting up of the data communication techniques in the deployment step is not feasible due to the variation of the situation. In order to maintain the required quality, sensor nodes should be able to modify their activity to compensate the negative impacts of the dynamic situation.

3.2 Suitable Existing CC Approach

In chapter 2, CC-T is formulated in a general platform composed of initialization, synchronization and data transmission steps. It is mentioned that the synchronization step is the most challenging part of CC-T and various synchronization methods are reviewed. Consequently, the focus of this section is on the synchronization approaches to find the one which has a high potential capability to acquire features which are mentioned for CC+.

Among the reviewed synchronization approaches, following ones are not capable to be applied as a basis for CC+:

- Full-feedback closed-loop has a centralized structure and so low scalability. It has also low flexibility as it needs to restart synchronization step in the case of any change in the position of the C-nodes.
- Time-Slotted Round-Trip has low scalability due to its high complexity.
- Master-slave is centralized in terms of the synchronization of the C-nodes with each other.
- (1+1)-EA method focuses on both phase and frequency. After some modifications, this method can be used as well. But it is relatively similar to OBCL. On the other hand, OBCL has been analyzed in the literature more. Therefore (1+1)-EA is not considered here.

In contrary, OBCL is iterative, hence it is flexible to work with different levels of synchronization accuracy. The entire C-nodes use the same channel to send their signal to the destination. Moreover, in comparison to other techniques, the destination performs less processing and communication load, thus it has a distributed structure and good scalability. The feedbacks are so short (one bit), so that it is relatively energy efficient. Therefore, OBCL matches the best to CC+ features and is utilized as a basis for further extensions. However, the current version of OBCL has some major drawbacks which are listed below:

- Similar to other CC approaches, it is applicable only in transmit mode. There are, however, situations like isolated nodes in which CC-T is useless because of the lack of C-nodes in the vicinity of the source. The extension of CC to receive mode would improve the network connectivity and data communication flexibility and reliability.
- Depending on the distance between C-nodes and destination, channel quality and transmission power level of the C-nodes, there is an optimum number of C-nodes. However in the current version of CC, there is no consideration to select the optimum number. Higher number of C-nodes results in energy waste whereas lower number causes low signal quality at the destination and so low reliability of data communication.
- There is not appropriate metrics to compare the capability of the nodes to join CC as C-nodes. Therefore, it is unrealistically assumed that the entire potential C-nodes have the same capability.
- C-nodes should individually receive the signals from destination. In addition, at the beginning of synchronization there is no improvement in the overall power received by the destination. More specifically, in the first iterations of OBCL, the destination does not receive higher power compared to the power received from individual C-nodes. All of these evidences prove that the destination should be in the coverage area of the entire C-nodes. So, the application of CC is mostly limited for reliability enhancement. However, CC+ should efficiently extend the transmission range as well.

In the remainder of this chapter, appropriate solutions for these drawbacks are proposed, implemented and evaluated.

3.3 Collaborative Communication at Receive Mode (CC-R)

Our first effort to develop CC+ is the extension of CC applications to receive mode. This new approach which is presented in:

- Performance analysis of receive collaboration in TDMA-based wireless sensor networks, Ubicomm 2010

is extensively discussed in this section.

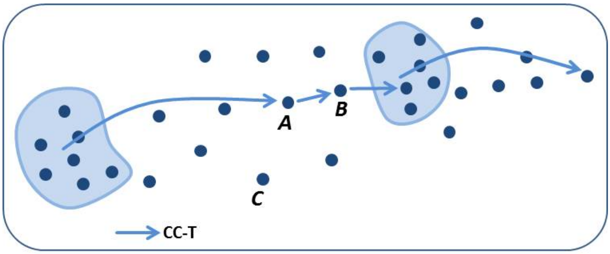
Collaborative communication at receive mode (CC-R) [BSB10a] [BSB10b] refers to the collaboration of a group of C-nodes to receive the signal of a remote source in a higher quality compared to the case that individual C-nodes act as receiver. The key enabling point of CC-R is the reciprocity in wave propagation and antenna patterns. According to reciprocity, antennas have the same pattern in both transmit and receive modes. This is valid for the overall pattern of the array antenna or C-nodes as well. Moreover, the transmission channel acts as a two-sided system i.e. if the positions of transmitter and receiver are exchanged, the receiver receives the same signal as before although the signal passes a reverse path (reciprocity).

During CC-R, C-nodes receive the signal of a source. One of the C-nodes, called *coordinator*, is responsible for the combination of the multiple versions of this signal. Therefore, C-nodes apply certain phase shifts on the signal which they receive and relay it to the coordinator. Provided that the phase shifts are properly estimated, the combination would be constructive and in comparison to the power level of individual C-nodes, the coordinator receives higher power level. Therefore, it is possible to improve the reception capability of C-nodes by the application of CC-R. Regarding reciprocity, if in the case of CC-T a certain set of phase shifts are achieved to improve the transmission power level through a certain remote node, the application of the same phase shifts in receive mode as CC-R is feasible. However, synchronization approaches can be utilized to initialize CC-R as well.

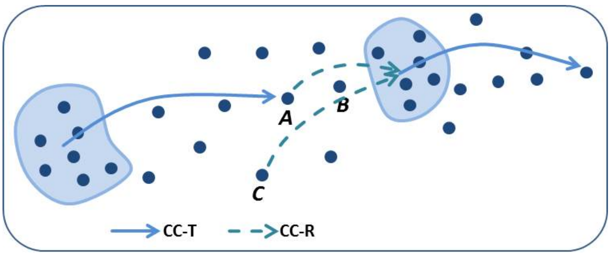
Figure 3.1 shows the impact of CC-R in a sample scenario. As seen in figure 3.1(a) data communication is only based on CC-T. Nodes A and B do not have enough neighbors to apply CC-T, thus they relay the message via a simple multi-hop path. Moreover, node C is isolated due to its long distance to the other nodes. But in figure 3.1(b) sensor nodes apply CC in both transmit and receive modes. In this case, node A individually sends its signal (as before) but there is a group of C-nodes which receive its signal via CC-R. Thus node B is jumped over. In addition, node C is not isolated anymore because of its CC-R oriented connection with the other nodes.

Figure 3.2 represents the relation of C-nodes, coordinator and source in CC-R. C-nodes receive the signal of the remote node in a low quality and during interaction with coordinator, estimate appropriate phase shifts. Then they receive messages of remote node, apply phase shifts and simultaneously send to the coordinator.

CC-R increases the network connectivity. In addition, it increases the data communication reliability and flexibility. Therefore, it would be an extension of CC to compensate for the inadequacies of CC-T. However similar to CC-T, when CC-R is applied, the source and C-nodes should be in the coverage area of each other, hence its application is limited to improve the reliability and signal quality.

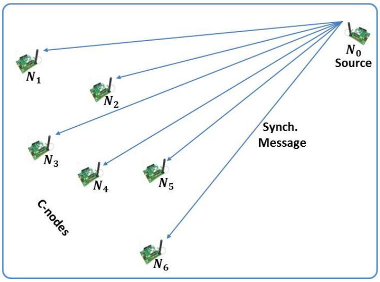


(a) Data communication when only CC-T is considered

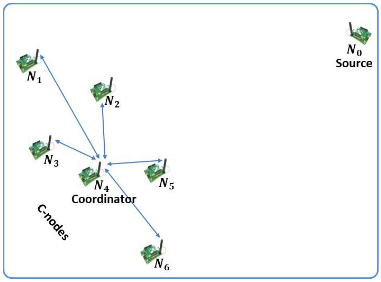


(b) Data communication when CC in both transmit and receive modes are considered

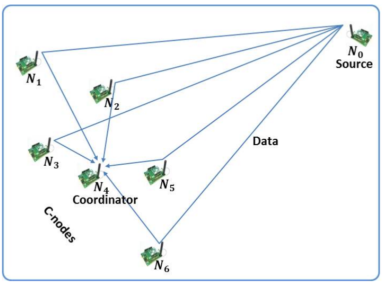
Figure 3.1: A sample scenario to show the impact of CC-R on the network connectivity



(a) C-nodes receive the signal of the source



(b) C-nodes interact to the destination for synchronization



(c) C-nodes relay the signal of the source to the destination after phase modification

Figure 3.2: A general view of CC-R

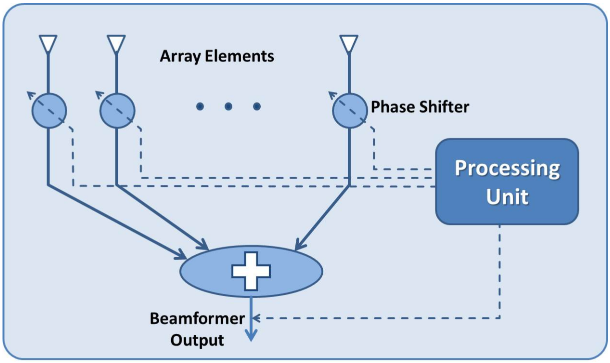


Figure 3.3: The standard structure of receive beamforming

3.3.1 CC-R Platform

As seen in figure 3.3, almost the same procedure is followed in receive beamforming. Comparison of these two techniques show that apart from the arrangement and connection of the C-nodes, CC-R and receive beamforming are similar. Therefore, it is expected that the existing techniques for receive beamforming such as:

- Directive reception which refers to the reception of the signal of a specific direction
- Channel equalization as a way to improve the reception capability in the case of severe transmission channel multi-path effects

can be realized in the form of CC-R. However, beamforming systems and sensor nodes have major differences which make the realization of CC-R more challenging:

- Array elements have known phase shifts because they are fixed in certain positions however C-nodes have unknown and random phase-offsets due to their random distribution and independent local oscillators
- In array elements coefficients are generated by a high power processor, but in CC-R coordinator generates appropriate coefficients.
- Array elements are wired to the processing unit whereas C-nodes are connected to the coordinator wirelessly. It might degrade the quality of multiple signals before they are combined.
- Array elements are arranged based on the type of signal they com-

municate and their operating angular interval but C-nodes are randomly distributed and their arrangement is not necessarily suitable to receive/send from/to a specific remote node.

In this section, we address these inefficiencies by definition of a general platform for CC-R. Similar to CC-T, CC-R is realized in three steps including initialization, synchronization and data communication.

3.3.1.1 Initialization

Initialization begins when a sensor node detects a source in its proximity but the signal it receives is not in an acceptable quality level. It broadcasts a message to its neighbors asking if they receive a high quality version of this signal. If so, it receives at least one feedback indicating an appropriate link to the source node, otherwise, as a coordinator, it sends another announcement to detect those of the neighbors which receive the signal of the source although in a low quality level. These nodes response the request and setup a group of C-nodes for CC-R.

3.3.1.2 Synchronization

Due to the reciprocity between CC-R and CC-T, almost all of the CC-T based synchronization approaches are applicable to CC-R as well. According to previous discussions, OBCL is selected as the major synchronization approach. In this section, it is modified to work in receive mode.

At the first iteration ($i = 1$), C-nodes apply random phase shifts to the signals which they receive from the source and simultaneously send them over the same channel to the coordinator. The coordinator receives the combination of the C-nodes' signals, estimates the overall SNR and keeps it as a reference value.

In the next iterations ($i > 1$) the same is performed. C-nodes apply a new set of random phase shifts to the signals they have received from the source node and relay them to the coordinator. Coordinator estimates the SNR of the overall signal it receives and compares it to its reference quality level. If higher quality is achieved ($SNR_i > SNR_{i-1}$), it sends a positive one-bit feedback to the C-nodes and changes its reference SNR to SNR_i. Otherwise a one-bit negative feedback indicating the improper phase shifts is sent to the C-nodes. In the case of positive feedback, C-nodes keep their phase shifts otherwise they cancel them. Iterations are continued until the signal of the source is received in an acceptable quality level. This procedure is continued until the required synchronization accuracy is achieved.

Other synchronization techniques which are presented for CC-T can be simply modified for CC-R as well. For instance, in the case of closed-loop full-feedback, C-nodes receive the signal of the source and relay it to the coordinator. Coordinator aligns the signals of the C-nodes and calculates the appropriate phase shifts which are reported to the C-nodes.

3.3.1.3 Aggregation

After synchronization is performed, source starts to send its data message. Each C-node receives the signal, modifies its carrier phases and relays it to the coordinator. It is worth noting that C-nodes do not detect the data sent by source. They just receive the signal, modify its phase and send the signal to the coordinator. Provided that the synchronization step is appropriately performed, a coordinator receives a constructive combination of multiple signals

In order to balance the power consumption of the C-nodes, the coordinator is randomly changed although the workload and energy consumption of the coordinator are not considerably higher than the other C-nodes. The phase shifts are valid as long as the position of the C-nodes and source are not changed considerably.

Table 3.1 summarizes the CC-R steps.

Table 3.1: Different steps of CC-R

Initialization	
Source	Keeps sending a request to find a relay node
Coordinator	Receives the signal of the source in a low quality
Coordinator	Asks its neighbors if any of which receive an acceptable version
Coordinator	If an acceptable version is not achieved, it broadcasts a request to its neighbors for joining as C-nodes
Synchronization (OBCL)	
First iteration $(i = 1)$	
C-nodes	Relay the signal of the source to the coordinator
Coordinator	Estimates the overall signal quality level (SNR_1) and sets it as the reference (SNR_{reff})
Next iterations $(i > 1)$	
C-nodes	Apply random phase shifts on their signals and send them to the coordinator
Coordinator	Estimates the overall quality level it receives (SNR_i)
	If $SNR_i > SNR_{reff}$
Coordinator	Sends a one-bit feedback
Coordinator	Considers SNR_i as the new reference
C-nodes	Keep the recent phase shifts
	Otherwise
Coordinator	Sends a one-bit negative feedback
C-nodes	Cancel the recent phase shifts
This iteration is repeated until the demanded quality level is achieved	
Aggregation	
Source	Starts sending of its data message
C-nodes	Receive the signal of the source, Apply proper phase shifts on the signal and Send them through the coordinator
Coordinator	Receives the combination of the multiple signals

3.4 Performance Evaluation

In this section, CC is investigated analytically and based on simulations in various aspects. The results and achievements of this section are presented partially in the following papers:

- On the feasibility of receive collaboration in wireless sensor networks, PIMRC 2010
- Collaborative channel equalization: analysis and performance evaluation of distributed aggregation methods in WSNs MASS 2011

As previously remarked, CC improves the network reliability and flexibility at the expense of an increase in the intra-nodes interaction for initialization and synchronization of C-nodes. In this section, at first the similarity of CC-T and CC-R in terms of their performance and costs is shown, then CC is evaluated in terms of energy consumption. At each scenario, one of the variants of CC (CC-T or CC-R) is considered. However due to their similarity the results are valid for both.

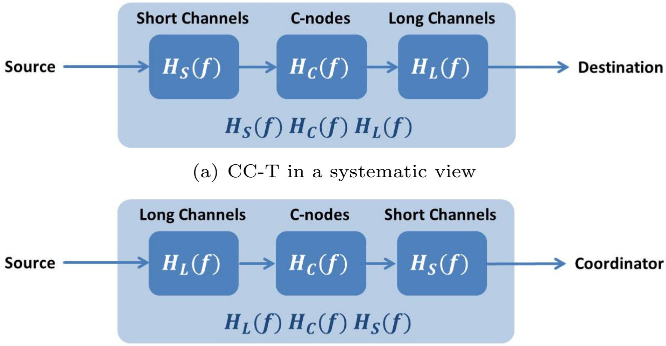
3.4.1 Comparison of CC-R to CC-T

The major structural difference between CC-T and CC-R is the position of C-nodes. In CC-T, C-nodes are in transmitter side at the vicinity of the source but in the case of CC-R, they are at the neighborhood of the destination (which acts as coordinator). The comparison of the interactions of CC-R and CC-T shows that the number of interactions is exactly the same, although the aggregation step seems to be different due to the different position of C-nodes.

As seen in figure 3.4, from a systematic point of view, the signal passes the three following systems during CC-R and CC-T:

- A short range channel between source/destination (in CC-T and CC-R respectively) and C-nodes ($H_S(f) = \alpha_S e^{j\phi_S}$)
- Phase shift and amplification in C-nodes ($H_C(f) = \alpha_C e^{j\phi_C}$)
- A long range channel between C-nodes and destination/source (respectively in CC-T and CC-R) and C-nodes ($H_L(f) = \alpha_L e^{j\phi_L}$)

The order of these systems is not the same in CC-R and CC-T. For CC-T, the signal passes first through short range channel, then the phase shifter in C-nodes and finally the long range channel. However, in the case of CC-R, there is first long-range channel, then phase shifter and finally the short-range channel. But as long as these systems are linear, different orders would not



(a) CC-T in a systematic view

(b) CC-R in a systematic view

Figure 3.4: Comparison of CC-T and CC-R in a systematic view

be problematic.

3.4.2 Impact of CC on Transmission Range

In this section, the capability of CC to extend the transmission range is investigated. In digital data communication, bit error rate (BER) is usually the major metric for describing the quality of a signal. According to [PS07], it is a function of transmission power level, modulation type and order, bit rate, pulse shape, and transmission channel fading and noise. For instance, in the case of *M-ray Pulsed Amplitude Modulation* (M-PAM) with Gaussian pulse shape, the probability of error (P_e) is calculated as follows [PS07]:

$$P_e \approx 2Q(\sqrt{2k\gamma_b}\sin\frac{\pi}{M}) \tag{3.1}$$

where:

M:	The modulation order,
γ_b:	Signal to noise ratio at the receiver, $\frac{L \cdot E_b}{N_0}$
L:	Path loss,
k:	$\log_2 M$
$Q(x)$:	Error function, $\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2} \cdot dt$

The transmission power which affects the signal to noise ratio, γ_b, is calculated as:

$$E_b = \int_T |S_t(t)|^2 \cdot dt \tag{3.2}$$

where $T = \frac{1}{R_b}$ and R_b is the bit rate. According to Friis equation [Fri46], transmission loss is calculated as:

$$L = (\frac{\lambda}{4\pi R})^{\alpha} \tag{3.3}$$

where R is the distance and α is a constant which reflects the environmental characteristics. In case of free space wave propagation $\alpha = 2$, but for other environments it takes other values. For instance, in dense urban areas it varies over $3 < \alpha < 5$. The modulation order, M, determines the number of bits which are carried by each communicating symbol.

According to equations 3.1 and 3.3 it can be said that the probability of error or BER depends on the distance between source and destination (R), bit rate (R_b) and transmission power level (P_{tr}). Among the effective parameters, R is usually fixed or out of control, but the other two factors (R_b and P_{tr}) can be modified by the transmitter as a tool to control either the signal quality at the receiver or the transmission range. The relation of the probability of error to γ_b for different values of M is depicted in figure 3.5.

It can be said that having a specific transmission power level, it is possible to extend the transmission range by decreasing the bit-rate or modulation order. It can be applied in CC to connect to a remote node which is out of the coverage area of the C-nodes. More specifically, before synchronization, interactions would be performed based on a lower bit-rate or modulation order. Therefore the capability of CC to extend the transmission range depends on the minimum acceptable bit-rate and modulation order.

The discussion of this section was based on M-PAM modulation technique. However, the comparison of BER formulas for various modulation techniques [PS07] confirms that in all digital modulation techniques, BER varies as a function of the distance between source and destination (R), bit rate (R_b) and transmission power level (P_{tr}). Therefore, the results achieved in this section can be generalized for all modulation techniques.

3.4.3 Minimum Number of C-nodes

The number of C-nodes is one of the effective parameters on the overall achievable transmission range as well as energy consumption in CC. In this section, the minimum number of C-nodes to gain a certain extension in the transmission range is analyzed. For this, we consider a WSN composed of similar sensor nodes with transmission range of R_i. As seen in figure 3.6, the

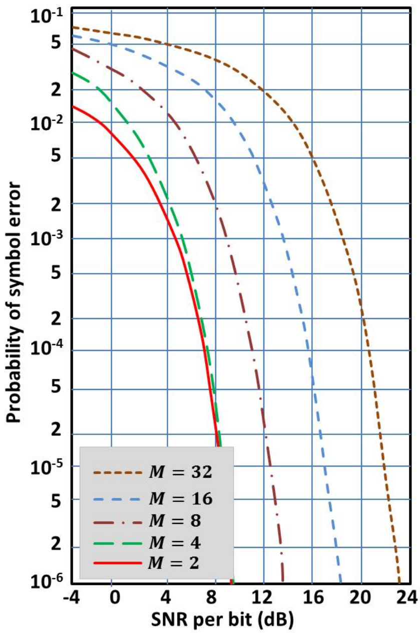


Figure 3.5: Relation of the signal quality to the received SNR and modulation order [PS07]

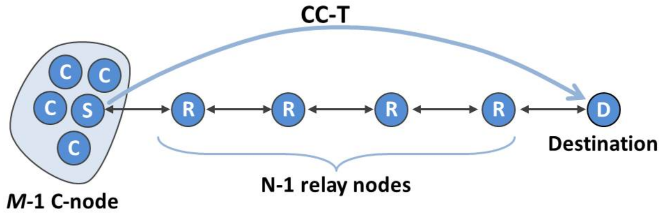


Figure 3.6: WSN model considered to extract the minimum number of C-nodes

goal is to connect certain set of source (S) and destination (D) with distance $R_d = NR_i$. In addition, CC-T and MH are compared in terms of the number of nodes (C-nodes in the case of CC-T and relay nodes in case of MH).

An ideal situation including:

- Relatively high density of the nodes so that:
  - Enough C-nodes are available to participate in CC-T
  - Relay nodes at the positions considered in figure 3.6 (over a straight line with distance R_i) to deliver messages with the minimum number of relays are available,
- Free space path loss,
- Perfect phase synchronization at C-nodes,

is considered. In the case of MH, there are $N-1$ relay nodes between source and destination. Therefore messages are transmitted N times before they are delivered to the destination.

In order to find the minimum number of C-nodes in the mentioned scenario, we calculate the minimum number of C-nodes to provide the same quality level at the destination as that of in MH technique. For this, it is assumed that M C-nodes are used during CC-T and the objective it to find the relation between N and M.

In case of perfect synchronization, the destination receives $S_{cc}(t) = \sqrt{\alpha_d} MS(t)$, where α_d is the transmission loss over a link of length R_d and $S(t)$ is the common signal sent by C-nodes. Therefore, the power level of the signal received by the destination is

$$P_{cc} = \alpha_d M^2 P_{tr} \tag{3.4}$$

where P_{tr} is the transmission power level of the C-nodes. On the other hand, in the case of MH, P_{mh}, the power level of the signal received by the destination is

$$P_{mh} = \alpha_i P_{tr} \tag{3.5}$$

where α_i is the transmission loss over a relay of length R_i. Provided that the destination receives the same power level at both cases of MH and CC-T:

$$P_{mh} = P_{cc} \tag{3.6}$$

therefore

$$\alpha_i P_{tr} = \alpha_d M^2 P_{tr} \tag{3.7}$$

or

$$\alpha_i = \alpha_d M^2 \tag{3.8}$$

The transmission loss α between two points of distance x is calculated as follows:

$$\alpha_x = \left(\frac{\lambda}{4\pi x}\right)^2 \tag{3.9}$$

where λ is the wavelength of the carrier frequency. After substitution of α from 3.9 into 3.8, we have:

$$(\frac{\lambda}{4\pi R_i})^2 = M^2(\frac{\lambda}{4\pi N R_i})^2 \tag{3.10}$$

or

$$M = N \tag{3.11}$$

In other words, in the mentioned ideal case the transmission range extension rate would be equal to the number of C-nodes. In addition, MH and CC need the same number of nodes (C-node in the case of CC and relay nodes in the case of MH) to cover a specific distance. The practical situation is, however, different from the scenario considered in this section. To gain the perfect synchronization is practically unfeasible. On the other hand, the assumption of being located in certain positions for relay nodes is not realistic. Therefore, in practice, the number of nodes to connect the mentioned source and destination via either MH or CC is more than what is calculated in 3.11.

In the other environments, like dense urban, there is an experimental form of Friis equation [Fri46]:

$$\alpha \propto \left(\frac{\lambda}{R_1}\right)^k \tag{3.12}$$

where k is the attenuation coefficient and is usually in the range of $3 < k < 5$. The number of C-nodes, M, for such environments is

$$M = N^{0.5k} \tag{3.13}$$

According to 3.13, in lossy areas, the number of C-nodes to access a certain destination is more than that which is calculated in 3.11 for free space path loss case.

3.4.4 Energy Consumption

In this section, the overall energy cost of CC when it is applied to communicate a message between a certain set of source and destination is calculated. It was discussed before that CC-R and CC-T are the same in terms of the number of interactions. Therefore, we calculate the energy consumption for one of which (CC-R). The results would be valid for another one as well.

Due to the random behavior of OBCL, the number of iterations to gain certain performance is not fixed. Furthermore, following a statistical approach to analyze OBCL-based CC is feasible only in a very simple and unrealistic scenario. Therefore, in this section full-feedback closed-loop method is utilized to the synchronization of C-nodes. According to this method, C-nodes receive the signal of the source, attach their ID to this signal and relay it to the coordinator. The coordinator extracts the signal of the entire C-nodes and estimates appropriate phase shifts to compensate the phase errors. The phase compensation information is then individually sent to the C-nodes. Apart from the data messages which are of length T_d, other communicated messages in CC-R are of length T_m. In addition, energy consumption during data processing or reception is neglected. Therefore, sensor nodes consume energy only when they send a signal.

In this scenario, M C-nodes (including coordinator) are randomly distributed with uniform distribution. The distance between source and coordinator is R_d and transmission range of individual sensor nodes is R_i. It is assumed that sensor nodes do not change their position during collaboration. In CC-R, the entire energy is consumed in the following three steps:

3.4.4.1 Initialization

In this step, source sends a message of length T_m through the C-nodes. Assuming E_{ini} as the energy consumption during this step, we have:

$$E_{ini} = T_m \cdot P_{tr} \tag{3.14}$$

where P_{tr} is the transmission power level.

3.4.4.2 Synchronization

During synchronization step, there are two kinds of interactions:

- The entire C-nodes send their signal to the coordinator.
- Coordinator sends the phase compensation information to the C-nodes.

In both of them, $M-1$ messages of length T_m are communicated. Therefore energy consumption during synchronization step E_{sync} would be:

$$E_{sync} = 2(M-1) \cdot T_m \cdot P_{tr} \tag{3.15}$$

3.4.4.3 Aggregation

At this step there are two kinds of interactions:

- Source sends its signal through the C-nodes ($T_d \cdot P_{tr}$).
- C-nodes relay the signal of the source to the coordinator ($(M-1)T_d \cdot P_{tr}$).

Thus the data communication step is composed of M interactions through which messages of length T_d are communicated.

$$E_{agg} = M \cdot T_d \cdot P_{tr} \tag{3.16}$$

As a result of the above analysis, the total energy consumption of CC-R is:

$$E_{CC-R} = E_{ini} + E_{syn} + E_{agg} \tag{3.17}$$

which is

$$E_{CC-R} = [(2M-1)T_m + MT_d]P_{tr} \tag{3.18}$$

This analysis is valid for different multiple access methods. However, in each method, there is a specific relation between signal quality (e.g. BER) at the receiver and transmission power level. Therefore, the multiple access method affects the required P_{tr}.

3.5 Collaborative Channel Equalization

One of the efficient applications of CC-R is Collaborative Channel Equalization (CCE) [BGS+11]. The version of CC-R which is discussed and analyzed so far is based on the assumption of line of sight (LoS) connection between source and C-nodes (similar to CC-T). However, in comparison, CCE is applied to more complex scenarios in which C-nodes receive the signal of the source via multiple paths from different directions. In such scenarios the signal of each C-node is a combination of multiple versions of the signal of the source with different time delays and variable coefficients. Therefore phase alignment and combination of multiple signals at coordinator would have low performance. CCE is applied to remove or decrease the undesired transmission channel effects. The structure of channel equalizer is identical to receive beamformer. However, channel equalization algorithms affect both phase and amplitudes of multiple signals. Therefore, instead of phase shifts, they generate complex weighting coefficients. After generation of the coefficients, they are sent by the coordinator to the C-nodes. During data communication, C-nodes apply these coefficients to the signal before sending them to the coordinator.

To generate the coefficients in CCE, certain features of the desired signal including pulse shape, modulation type, statistical characteristics, etc. are applied to align and weight multiple signals so that those components of multiple signals which possess the desired features constructively combine. Since such components are versions of the signal of the source, CCE output has higher correlation with the signal of the source or equivalently, CCE output has higher quality compared to the signal of the individual C-nodes. Depending on the application, different features of the signal might be applied for channel equalization. In case of digital signals, (quasi-)constant envelop or the certain piece of codes which are frequently repeated (like PN-codes in CDMA) are utilized. In most channel equalization techniques, weighting coefficients are recursively calculated.

3.5.1 Signal and Channel Model

The arrangement of C-nodes, coordinator and source is more or less the same as what we considered to evaluate CC-R. M C-nodes are randomly deployed with uniform distribution. Source is at the distance of R_d from the coordinator and its signal is received by the C-nodes in a very low quality. The transmission channel is a multi-path Rayleigh fading channel [RR02] with additive white Gaussian noise (AWGN). Signal of the source is received by C-nodes in multiple components within an angular interval centered by the LoS direction with normal distribution. Sensor nodes use DS-CDMA for data communication and each one allocates a unique and fixed PN-code. Hence PN-codes can be interpreted as the nodes' IDs as well. The minimum length of PN-codes is $round(\log_2 M) + 1$ where $round()$ is the integer part of the number. But the length of PN-codes might increase in order to enhance the signal quality. Here it is assumed that sensor nodes (both source and C-nodes) utilize the minimum length of PN-codes.

The vector of k-th sample of signals received by C-nodes (including the coordinator), $\mathbf{x}_k$, is as follows:

$$\mathbf{x}_k = [x_1(k), x_2(k), \cdots, x_M(k)] \tag{3.19}$$

where $x_i(k)$ is the k-th sample of the signal received by the i-th C-node. The formulations of this section are presented in discrete domain although the signals and processes are partially in analog domain.

3.5.2 Least Square Constant Modulus Algorithm

Least square constant modulus algorithm (LS-CMA) [CLNCX04] [Age86] is one of the efficient algorithms for digital signal applications. This algorithm focuses on the constant envelope of the digital modulated signals and tries to maximize the power of the constant envelope components of multiple signals. For this, LS-CMA utilizes the following cost function [Age86].

$$J(\mathbf{w}_k) = E[(|y_k|^2 - 1)^2] \tag{3.20}$$

in which $E()$ indicates the expected value, $\mathbf{w}_k$ is a $1 \times M$ vector containing weighting coefficients at k-th instance:

$$\mathbf{w}_k = [w_1(k), w_2(k), \cdots, w_M(k)] \tag{3.21}$$

and y_k is the output of the channel equalizer:

$$y_k = \mathbf{w}_k \cdot \mathbf{x}_k^H \tag{3.22}$$

Here, $()^H$ is the complex transpose operator. Weighting vector is recursively updated based on its previous value and the channel equalizer output as follows:

$$\mathbf{w}_{k+1} = \mathbf{w}_k - \mu \mathbf{x}_k (|y_k|^2 - 1) y_k \tag{3.23}$$

μ is the step size which controls the convergence rate of the algorithm. Depending on μ, the weighting coefficients approach their optimum values after several iterations including equations 3.22 and 3.23. After convergence, the weighting coefficients will have no considerable variation over time. Therefore, depending on the rate of transmission channel variation, these coefficients are valid for a certain period of time.

3.5.3 Performance Analysis of Collaborative Channel Equalization

In this section the positive impact of CCE on data communication performance is studied. Various metrics might be considered to evaluate the signal quality but since digital signals are utilized, BER would be more accurate. As the first analysis, the BER of the channel equalizer output as well as the average BER of signals of C-nodes are represented and compared in figure 3.7. In this experiment, $M = 9$ C-nodes collaborate with the coordinator. DS-CDMA with PN-codes of length $L_C = 16$ is applied to data communication however, the entire BER values are calculated before de-spreading. The source generates a random bit stream of length $L_d = 1000$ and after de-spreading sends it through a Rayleigh AWGN channel. Each C-node receives this signal statistically in 5 rays with different power levels and time delays.

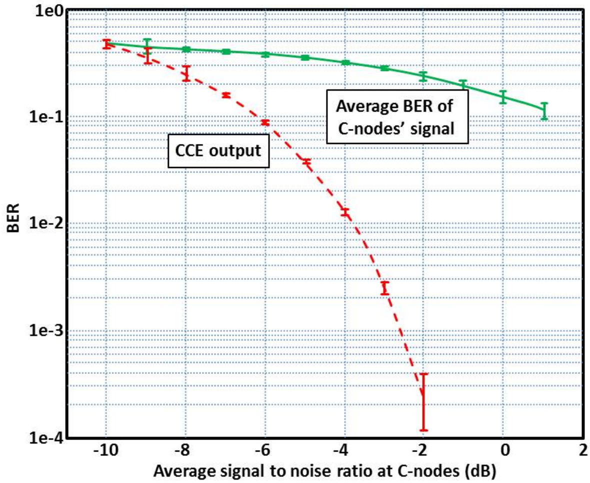


Figure 3.7: Comparison of the signal quality in terms of BER with and without the application of CCE

The coordinator uses LS-CMA based channel equalizer. This experiment is repeated 500 times and averaged to get reliable results.

In figure 3.7, X-axis represents the SNR of the transmitted signal by the source and Y-axis represents BER. Solid curve represents the average BER of the signal received by the C-nodes whereas dashed curve shows the BER at the coordinator after the application of CCE. BER values are calculated before de-spreading. Therefore, the improvements are only caused by the channel equalization. This figure shows that due to severe channel effects, even increasing of the power level is not an efficient way to improve the BER rate at the C-nodes. In the case of individual reception, their average BER levels are in the range of 0.5 for average SNR level of $-10dB$ to 0.1 for $1dB$. However, CCE presents higher performance and the distance between the two curves increases by increasing of the average SNR. Considering higher values of SNR level, the BER of the channel equalizer output descends to zero while without the use of CCE, BER still gets 0.1.

Figure 3.8 CCE is evaluated in another scenario. Different levels of BER at the destination (Y-axis) are considered and the objective is to find the minimum number of C-nodes to satisfy it (X-axis). In the previous simulation, it is proved that the performance of CCE varies as a function of average SNR in the C-nodes. Therefore, this simulation is repeated for different values of average SNR at C-nodes (values on the curves). As expected, the signal

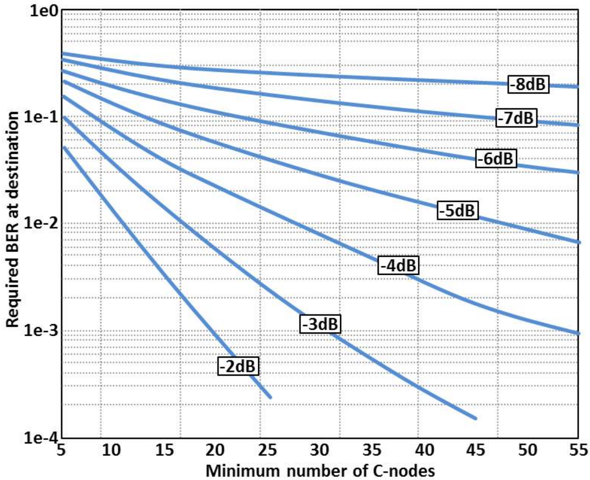


Figure 3.8: Impact of the number of C-nodes on BER (Labels of the curves represent the average SNR at C-nodes)

quality at the output of CCE increases by the increasing of the number of C-nodes. In addition, as the SNR gets higher, the slope of the curves increases and the BER decreases at the higher rate. This means that the application of CCE for higher numbers of C-nodes as well as higher SNR levels would be more efficient. More analyses about CCE are presented in [BSB10a].

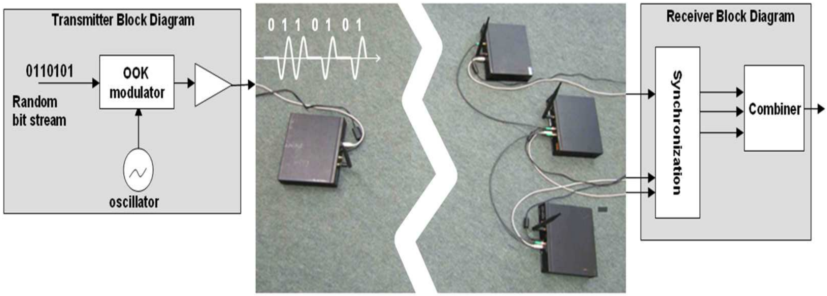
3.6 Experimental Analysis

The results of an experimental analysis of CC are represented in this section.

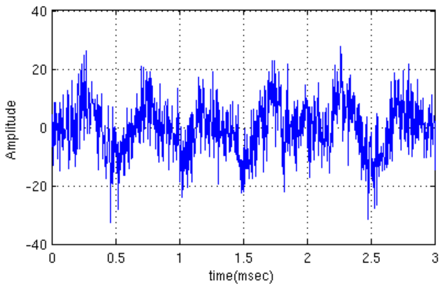
3.6.1 Scenario

Figure 3.9 represents the experimental scenario. Each sensor node is composed of a laptop as the processing and monitoring unit and a USRP software radio as RF and antenna unit. Therefore, it is possible to monitor and process the signals which are communicated among the sensor nodes.

In this experiment, three C-nodes are applied. The arrangement of C-nodes, as well as the source, is illustrated in figure 3.9(a). Assuming the position of the source as reference $(0, 0)$, C-nodes are located in respectively $(479\ cm, 24\ cm)$, $(495\ cm, -11\ cm)$ and $(500\ cm, 13\ cm)$. A random data



(a) Test scenario: relation of the USRPs (center), transmitter block diagram (left) and receiver block diagram (right)



(b) Sample received signals by the receiver USRPs

Figure 3.9: Experimental performance evaluation of receive collaboration

stream of 5000 *bits* and rate of 10 kb/s is modulated with On-Off Keying (OOK) technique. The source up-converts this signal to 900 MHz and broadcasts it via an omni-directional antenna. C-nodes receive the signal and after synchronization, simultaneously send their signals to the coordinator.

The idea of this experimentation is to represent the performance of CC in terms of the signal quality and data communication reliability. Therefore different signal quality levels are needed at various C-nodes. To simulate this, techniques such as bending of the C-nodes' antennas or blockage of the signals by putting absorbers between source and C-nodes are applied. One sample signal of C-nodes is represented in figure 3.9(b). Different signal qualities are partially visible in this figure.

Table 3.2: BER level at various antennas for different cases

Cases	BER_1	BER_2	BER_3	BER_I	BER_II
Case A ($t = 0$)	0.3296	4.8e-4	0.0102	2e-5	2.6e-4
Case B ($t = 1h$)	0.3913	0.0043	0.0164	6e-5	0.0018
Case C ($t = 2h$)	0.399	0.0086	0.024	3.2e-4	0.0055

3.6.2 Experimental Results

The BER of the signals of the individual C-nodes are represented in table 3.2. As seen, N_1 has a low quality as its BER levels are over 0.3. But the other two nodes receive a relatively good quality levels. In order to show the repeatability of the experiment, it is repeated two times after one and two hours and the results are represented in table 3.2 as well. The two sets of C-nodes are considered for collaboration:

- Set I: Nodes N_2 and N_3
- Set II: The entire nodes

The results of this experiment approve of the positive impact of CC-R on signal quality and reliability which are discussed as follows:

3.6.2.1 Signal Quality

The BER of the C-nodes in set I and II and their collaboration results (BER_I and BER_{II}) are compared in table 3.2 and figure 3.10. In this figure, BER levels are presented in logarithmic scale. The CC-R output (BER_I and BER_{II}) has a better performance which proves the positive impact of CC-R. This experiment shows that although the signal quality at the entire C-nodes of set I is acceptable, the application of CC-R to gain higher signal quality (lower BER) is feasible. The improvement allows the remote node to be in a farther distance.

3.6.2.2 Reliability

In order to show the positive effect of CC-R on the reliability of data communication, the signal quality at node N_1 is impaired by bending the antenna. Comparison of its BER to the other C-nodes shows its low quality. In practice, other reasons like noise sources in the vicinity of C-nodes, blockage or lossy channels might also negatively affect the BER. If node N_1 is individually considered as the receiver, it receives a very low signal quality which is

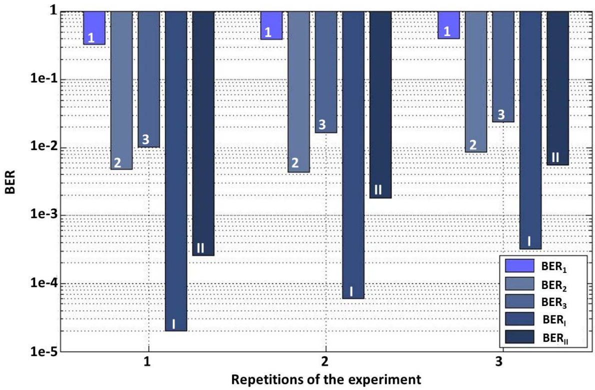


Figure 3.10: Comparison of the BER level of C-nodes and CC-R output of set I and II

not acceptable. But when it collaborates with the other nodes of set II, the signal quality improves. The collaboration results of the C-nodes of set II are presented in the last column of table 3.2 and figure 3.10. As seen, despite of the low signal quality of N_1, the overall BER is lower than that of the entire C-nodes (higher quality). In other words, CC-R not only compensates the low quality of the signal of N_1, it improves the overall signal quality compared to N_2 and N_3. Since the transmission channel continuously varies over time, the quality decrease might occur for each of the C-nodes. But according to space diversity in CC-R, the probability of having low quality at the entire C-nodes and so in the CC-R output is relatively low.

3.7 Ideas for Adaptive Improvement of the CC Performance

The major focus of the existing efforts in the area of CC is to improve the performance of the synchronization approaches in terms of energy consumption, accuracy, robustness and distribution of the workload of CC among participating nodes. Despite of their positive effects on the performance of CC, there are still inefficiencies mostly due to unrealistic assumptions about sensor nodes and WNSs. In this section, several ideas are proposed to improve the performance of CC. The major goal of these ideas is to minimize and equalize the energy consumption during CC-based data communication among certain nodes. In addition, to make the ideas applicable for further development in the next chapters, autonomous algorithms are introduced to implement the ideas for CC. The achievements of this section are partially presented in

- Self-optimized collaborative data communication in wireless sensor networks, ACM workshop Organic Computing as part of ICAC 2011

One of the unrealistic assumptions about sensor nodes which negatively affects the CC performance is the assumption of similar capabilities of sensor nodes to attend the CC. But there are several reasons why this assumption is invalid:

- Nodes located in hot spots have lots of data to report and consume their energy resources sooner.
- Some nodes might have higher priority due to possessing special sensors. So they have less activity in terms of networking.
- Transmission channels of nodes located close to the noise sources or behind the obstacles have significant effect on their data communication quality.
- Nodes with low energy level at their batteries are not good candidates to participate in networking activities as it results in the deactivation of some nodes within the coverage area.

In addition, at each scenario the entire potential C-nodes are applied to CC but it is not a reasonable decision. Depending on the status of the nodes and channel as well as the required quality and the distance between source and destination, there is an optimum number for C-nodes. If the number of C-nodes is more than the optimum number, although the destination would receive higher signal quality but it is considered as energy waste. On the other hand, the application of the fewer nodes for CC results in lower quality than what is required.

In order to solve these challenges, appropriate metrics to evaluate the capability of the potential C-nodes are defined. Potential C-nodes estimate their overall rank and based on a distributed performance comparison decide if they are suitable nodes for collaboration [BMSB11], i.e. sensor nodes find the optimum set without external help.

3.7.1 Application of Effective Factors to CC

In this section, the entire algorithms are explained for CC-T. The only difference when CC-R is considered is that the tasks of source and destination are performed by coordinator and source, respectively.

3.7.1.1 Ranking of the Potential C-nodes

In CC-T, source begins the collaboration by broadcasting a message to its neighbors to participate in CC and those of the neighbors which receive this message, join CC. The idea is to enable sensor nodes to estimate their rank among the entire potential C-nodes and join CC as C-node only if their rank is high than a threshold which is set by source.

In order to realize this idea, it is necessary to define *effective metrics* [BMSB11] to evaluate the nodes' capability. There are various effective metrics which might change the capability of C-nodes for participating in CC. Some metrics such as transmission channel effects, noise level at the proximity of the C-nodes or defected sub-systems at C-nodes directly affect the signal quality (BER) during data communication. However, there are other metrics which do not have direct effect on the signal quality but have determinant role in the capability of the C-nodes for collaboration. For instance, low energy storage at nodes does not directly affect the signal quality or performance of CC, but it causes early death of some nodes and leads to the generation of holes within the coverage area. Each metric has a certain weight in the overall grade which is also defined in advance.

In order to apply effective metrics to select capable C-nodes for CC, it is suggest that the source sends a primary threshold level together with its announcement for joining CC. Sensor nodes estimate their grade in each of the effective metrics and calculate their overall grade. They participate in the CC only if their grades are higher than the threshold.

3.7.1.2 Selection of the Minimum Number of C-nodes

Determining the minimum number of C-nodes would be an iterative process. The primary threshold level which is set by the source is more or less random and is not necessarily an appropriate one, however it is corrected during iterations with destination. Those of the potential C-nodes which have higher ranks compared to the threshold, work as C-nodes.

The optimum number of C-nodes is achieved based on the interaction between destination and C-nodes. C-nodes which are selected in the first iteration interact with the destination for synchronization. After gaining the required accuracy, the destination reports its signal quality level to the C-nodes. The source modifies the threshold based on the feedback of the destination. If the power level at the destination is higher than the desired level, the source estimates and broadcasts a higher threshold to limit the number of C-nodes. Those of the C-nodes whose rank is lower than threshold stop acting as C-node. But if the destination's feedback indicates a lower power level than the

Table 3.3: CC+ in transmit mode: it contains procedures to select the minimum number of highest rank nodes

Initialization	
Source	Broadcasts a request including the threshold to find potential C-nodes for CC
Pot. C-nodes	Estimate their grade in the preset metrics
Pot. C-nodes	*If* (grade ¿ threshold) join CC, *else* go to the standby mode
Synchronization and node selection	
C-nodes	Synchronization
Destination	Sends feedback to report its signal quality level.
	If (signal quality is lower than the expected level)
Destination	Sends a negative feedback
Source	Broadcasts a lower threshold
Pot. C-nodes	*(* grade ¿ new threshold) join CC
	Else
Destination	Sends a positive feedback
Source	Broadcasts a higher threshold
C-nodes	*If* (grade ¡ new threshold) leave CC
Data transmission	
C-nodes	Receive data from the source and after phase modification, relay it to the destination

desired level, a lower threshold is broadcast by the source which allows new nodes to join the process as C-node. The process continues until the required power level at the destination is achieved. C-nodes selected based on this method have:

- The highest capability because they have the highest rank among the others
- The minimum number because they are chosen iteratively out of the highest ranked ones

During collaboration, due to the variation of the transmission channel or sensor nodes' situations, the optimum value of M may change. Proper feedbacks from the destination allow the source to autonomously re-optimize this parameter. The proposed algorithm is reviewed in table 3.3.

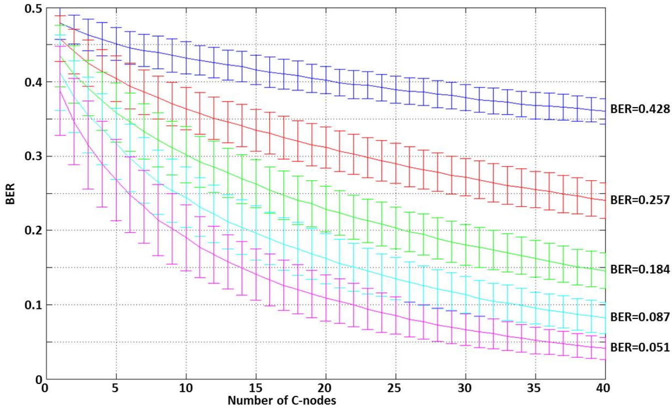


Figure 3.11: Impact of the selection of the best M nodes on the collaboration energy efficiency: 40 nodes participate in the collaboration and only M of them are selected

3.7.1.3 Performance Analysis

In this section, we evaluate the positive effect of the node selection approach. For this, it is assumed that a specific set of source and destination utilizes CC-T for data communication. As the first analysis, $M_0 = 40$ potential C-nodes with different signal quality are available to join CC-T. This difference can be due to either transmission channel or defections in the sensor nodes. Potential C-nodes are ranked based on their BER and M of the highest ranked ones when M varies in the range $[1, M_0]$ are selected as C-nodes. The source generates random bit streams of length 1000 and shares them among C-nodes. Since in this examination, the goal is to evaluate the performance of node selection approach, a perfect synchronization is considered. In order to achieve reliable results, we have repeated and averaged each test 100 times.

The results are presented in figure 3.11. Y-axis represents the achievable BER at the destination when M C-nodes from the highest ranked candidates (X-axis) are selected. Different quality levels for potential C-nodes are considered and each curve corresponds to a specific average quality level. At the entire quality levels, the BER of the CC-T output decreases by the increasing the number of C-nodes. However, the slope of the curves decreases by increasing M. Since highest ranked nodes are selected first, BER curves decrease very fast at the beginning. But, after increasing M, the participating nodes do not increase the quality, therefore they do not show a considerable positive effect on the overall BER. The same pattern is observed in the entire curves. However as expected, curves corresponding to lower signal quality levels vary

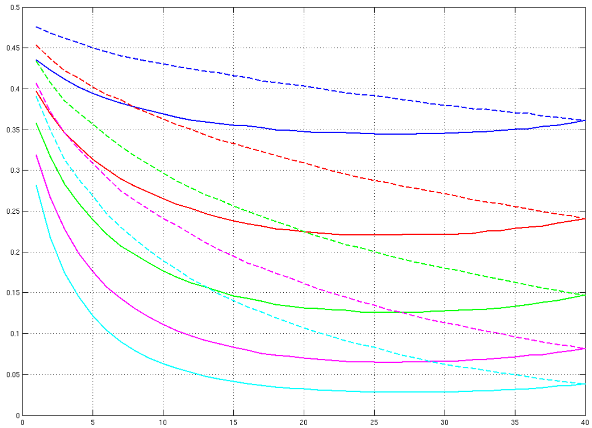


Figure 3.12: Comparison of the minimum number of C-nodes to gain different levels of BER for the proposed and conventional methods

at higher BER ranges. It is worth noting that the number of C-nodes to gain a specific BER directly affect the energy efficiency. Therefore, this figure also shows positive impact of the new idea on the energy efficiency of CC.

In another examination, the efficiency of the proposed approach is compared to the conventional method in terms of the minimum number of C-nodes to gain different values of BER. Results are represented in figure 3.12. Y-axis is the expected BER at the destination whereas X-axis represents the minimum number of C-nodes (M) to gain the BER. The dashed curves correspond to the conventional approach in which M random C-nodes out of the $M_0 = 40$ potential ones are selected, however in solid curves the new approach is considered which is based on the ranking of the potential C-nodes before selection. In addition, the test is repeated for different quality levels which are recognized in different colors. BER value mentioned for each color is the average BER at potential C-nodes. Similar setting to that of figure 3.11 including bit streams of length 1000 as well as 100 times repetition of the test and averaging is considered.

In comparison, the curves representing the BER of the proposed method decrease faster at the beginning of the curves (small values of M). In other words, in the proposed technique to gain a certain value of BER, less C-nodes are needed which results in less energy consumption. Since sorting of the nodes is based on their corresponding signal quality, the first signals have the highest quality. Therefore, in comparison to the case of random selection (conventional method), their collaboration yields lower BER. But by increasing M, the new joined signals in the proposed method would have lower quality. Therefore, after some increase of M, the effect of the new C-nodes is slightly positive whereas at the last part of the curves the impact of the added nodes is even destructive. The reason is the decrease of the nodes' capability by increasing M. This result is also approved by the experimental analysis of section 3.6. Comparison of the collaboration results in sets I and II in table 3.2 shows that the low quality node (N_1) has a negative effect on CC performance. In the entire repetitions of the experiment, collaboration of set I, results in higher signal quality.

3.7.2 Regulation of the Energy Consumption

Although sensor nodes have the same energy storage when they are deployed, due to some reasons including being located at the hot spots or at the vicinity of strong noise sources as well as having lossy transmission channels with other nodes, their energy consumptions are different. Thus they will have different energy storage levels. If critical sensor nodes continue their normal activity, they would exhaust their energy storage sooner than the other nodes. It leads to the early death of such nodes which degrades the WSNs performance by leaving holes in the coverage area.

CC improves the energy regulation in WSNs as data communication is performed by a group of nodes. However, a higher level of energy balance is still possible by considering the energy storage level as a metric to select appropriate C-nodes for CC. In this case, sensor nodes with low energy levels will have low grades, thus they are not considered as capable sensor nodes for collaboration. It decreases the activity of such nodes which automatically let them maintain their energy.

Figure 3.13 represents the improvement in balancing battery exhaustion by considering the energy storage level as a metric in the node selection process. In this figure, it is assumed that in a WSN composed of 500 sensor nodes, data transmission is performed collaboratively with $M = 50$ C-nodes. For the ease of simulation, it is assumed that the entire messages have the same length. Since the entire nodes have the same transmission power level, communication of each message costs a fixed amount of energy for the C-nodes. The M C-nodes are selected from the M_0 potential ones where $50 < M_0 < 90$. Without loss of generality, it is assumed that even if some nodes at the proximity of the source are exhausted, there are enough neighboring nodes to satisfy the assumptions of this analysis. Furthermore, it is assumed that source sends one message per unit time. Since the number of C-nodes is always fixed, the overall energy consumption is the same for the entire situations (different values of M_0). The examination ends when only 20% of the nodes are exhausted.

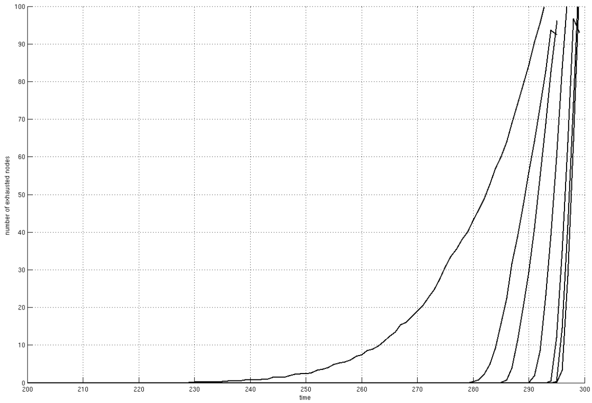


Figure 3.13: Illustration of the positive impact of the proposed algorithm on the lifetime

The Y-axis of figure 3.13 represents the number of exhausted nodes over time (X-axis). Each curve indicates a specific number of M_0. At the beginning, the entire nodes have the same situation and have enough energy storage in their batteries. So, there is no preference and M C-nodes are randomly selected from the M_0 potential ones. In this period of time ($t < 220$) no death node is reported. In the conventional method ($M_0 = 50$) even after the network activity and changing of the energy storage levels of the potential C-nodes, there is no priority to select C-nodes and because of this a low performance is presented. As seen, in the period in which none of the other curves report death nodes ($t < 280$), in the conventional approach more than 30% of the nodes are death. However in the proposed approach ($M_0 > 50$), energy consumption in the network is quit regulated so that in a large interval of the network lifetime the entire nodes are active. This capability is achieved by the consideration of the available energy storage as the metric for the selection of C-nodes. In addition, the performance of the proposed approach enhances by increasing M_0 so that in the case of $M_0 = 90$ in 96% of lifetime there is no death node. The reason is the higher degree of freedom to select the most capable C-nodes in higher values of M_0.

3.8 Summary

The investigations of this chapter to achieve a high performance CC technique results in CC+. It enables C-nodes to collaborate in both receive and transmit modes. In addition, it has a distributed and scalable structure while OBCL synchronization is applied. During CC+, the minimum number of high ranked C-nodes is selected. Therefore the process is highly energy efficient and due to the interaction of C-nodes with the remote node (source in CC-R and destination in CC-T) during node selection, the required signal quality at the destination is guaranteed.

The enhancement of the reliability and the flexibility are considered as the major objective of data communication in WSNs. CC+ has an inherently high level of reliability due to the application of collaborative approach for data communication. However in comparison to other CC techniques, it possesses even a higher level of reliability due to the development of CC-R and increasing the usability of CC. On the other hand, the node selection approach in CC+ increases its flexibility to match to various objectives or dynamic situation of WSN by the selection of appropriate and application-specific metrics. In the next two chapters, CC+ will be integrated to multi-hop and mobile WSNs.

Chapter 4

Multi-Hop Collaborative Communication (MH-CC)

In the previous chapter, an efficient version of Collaborative Communication (CC), dubbed CC+, was developed which is applicable to both receive and transmission modes. In addition, CC+ determines and applies the minimum number of collaborative nodes (C-nodes) after it ranks the potential ones based on their capabilities. Since a recursive procedure is considered for regulating the number of nodes, the minimum number of C-nodes is selected automatically. Based on the analysis carried out in chapter 3, it can be said that CC+ outperforms other CC approaches in terms of energy efficiency, scalability, reliability and flexibility. However, similar to other CC techniques, it is still limited to single-hop scenarios in which communication between a specific pair of source and destination is considered.

In this chapter, CC is integrated to multi-hop (MH) networks to improve the flexibility and reliability of data communication in large scale MH networks. In addition, the problem of limited transmission range extension of existing CC approaches which was previously discussed is resolved by the integration of CC to MH routing protocols. The proposed ideas are formulated as a routing protocol called Multi-Hop Collaborative Communication (MH-CC). The achievements of this chapter are partially presented in following papers:

- MH-CC: multi-hop collaborative data communication in WSNs, PIMRC 2013,
- A realistic hop-cost model for distance vector routing in ad-hoc wireless sensor networks, INSS 2012
- Transmission channel sensitive multi-metric routing for WSNs, ICWCUCA 2012,

4.1 Impact of MH-CC on Sensor Nodes' Activity

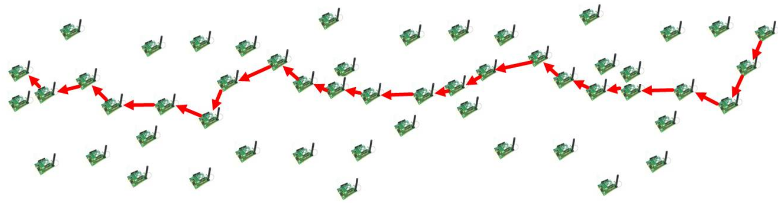
MH-CC enables sensor nodes to extend their transmission range in a certain direction by the development of CC sessions. It improves the network connectivity and data communication reliability as data is transmitted via a group of C-nodes. In addition, by the extension of the length of the links, it simplifies the routing approaches.

In figure 4.1, a specific pair of source and destination is considered which are meant to connect to each other and communicate data. Two different networking approaches: MH and MH-CC are considered. As seen in figure 4.1(a), in case of MH the data of the remote source is received by the destination after relatively large number of relays which is highly unreliable due to the dynamic situation of the sensor nodes. In addition, both discovery and maintenance of such long paths are quite resource demanding and challenging. However, MH-CC (figure 4.1(b)) allows groups of C-nodes to directly communicate to the relay nodes which are several times farther than those in simple MH. Therefore, in comparison, MH-CC results in a simpler routing approach with higher reliability and flexibility.

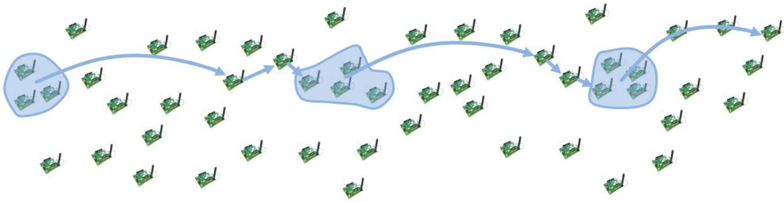
In addition, the dynamic situation of WSNs due to either the mobility of sensor nodes as well as various obstacles among them or the deactivation of sensor nodes because of battery depletion changes the network topology. MH-CC can be applied to compensate such topological changes in the network by regulating the transmission range. On the other hand, the data communication objectives in a certain WSN might vary over time. For instance, in a fire alarming application, there are two different modes:

- **Surveillance mode:** network activity is quite energy efficient because fire does not happen very often and this mode lasts for a relatively long time. Thus energy efficiency has the highest priority.
- **Alarm mode:** A fire or a potential situation for fire is detected. To minimize the damages, critical situation should be reported with the highest possible delivery rate and reliability because sensor nodes have limited time before they are burnt. In addition, due to the sudden change of the temperature, lots of nodes try to report their data simultaneously.

MH-CC is applicable to match the WSN to the network objectives by changing the network topology. Although simple MH might be an appropriate solution for surveillance mode, however, in alarm mode sensor nodes apply CC with the highest possible transmission range to deliver their message to the destination at the maximum possible rate.



(a) The large number of relays in MH path results in low reliability



(b) MH-CC simplifies the routing approach and increases the network connectivity

Figure 4.1: Comparison of data communication in MH and MH-CC in extended WSNs

4.2 Challenges Behind MH-CC Routing

MH-CC routing is not a specific routing algorithm but a new platform which enables a large family of the existing routing algorithms to apply CC as a tool to increase the length of relays along the paths between sources and destinations. In this section, major challenges behind the application of CC in multi-hop networks are addressed:

- **Directive unknown pattern:** This is the major difference between simple MH and MH-CC data communication. Sensor nodes have omni-directional patterns. Therefore in the case of individual data communication, their pattern is fixed and is independent of direction of the destination. However, when sensor nodes communicate collaboratively, their overall pattern would be directive pointing to the destination. In addition, the overall beam-pattern is affected by the number and position of C-nodes as well as their carrier phases. Moreover, except for the case of absolute location-awareness (C-nodes are aware of their absolute location), C-nodes are not aware of the direction of their overall beam pattern or appropriate phase shifts to direct their pattern to a certain direction.

- **Direction of the target:** In MH-CC, the remote node (source in CC-R or destination in CC-T) is not accessible in advance since CC is not established yet. However, to establish CC it is necessary to contact the remote node.

- **High complexity of route discovery in MH-CC:** It is mainly because of the large number of potential relay nodes due to the extended transmission range. To figure out this problem, assume in a WSN with density d, M C-nodes of transmission range R_i collaborate in form of CC-T. According to previous discussions, in case of perfect synchronization the final transmission range would be $R_{CC} = M \cdot R_i$ which covers an area including $d\pi(MR_i)^2$ nodes. Regarding the fact that all of the sensor nodes in the coverage area are considered as potential relay nodes, the process to discover appropriate one would be so complex. The reason is that the number of potential relay nodes is proportional to the second power of M and R_i. The difference between the number of potential relay nodes in the cases of MH and MH-CC is compared in figure 4.2.

- **Low capability of CC to extend the transmission range:** As mentioned before, existing CC approaches are based on the individual interaction of C-nodes with destination (in CC-T) or source (in CC-R) especially in synchronization step. Therefore, such techniques are not suitable for transmission range extension although they prove high

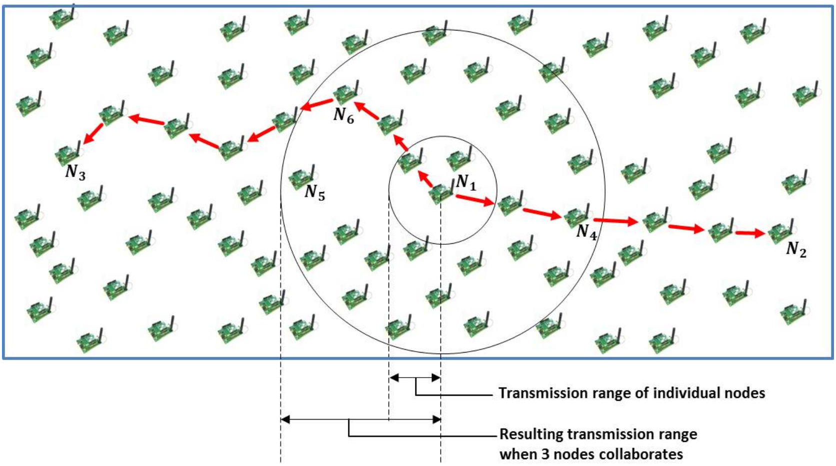


Figure 4.2: Comparison of the number of potential relay nodes in MH and MH-CC (for $M = 3$ C-nodes)

efficiency to enhance reliability. The reason is that transmission range extension is a necessary feature MH-CC should possess for topology control approaches.

4.3 MH-CC Routing

Before the introduction of MH-CC routing algorithm, the following terms are defined. These terms are also represented in figure 4.3.

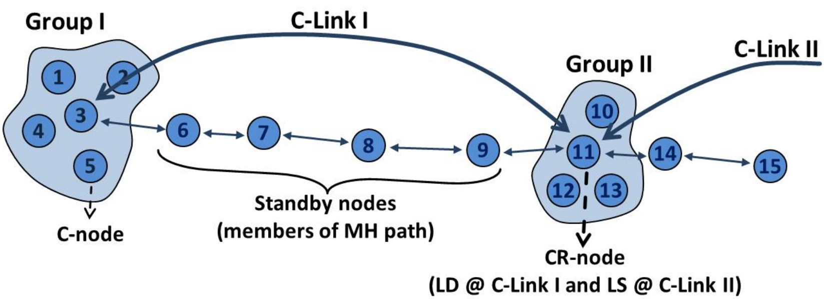


Figure 4.3: Different elements of a MH-CC path

Collaborative Relay node (CR-node): A relay node which is accessible only using CC. It works as a destination to receive the signal of a group of C-nodes (CC-T) or as a source to send its signal to another group of C-nodes (CC-R).

Local Destination (LD) and **Local Source (LS):** CR-nodes act as destination to receive data from group of C-nodes and then as a new source, share the data among their corresponding C-nodes to send the data to the next CR-node. In order to distinguish them from the main source and destination, we call them local destination (LD) and local source (LS). In figure 4.3, node N_{11} acts as LD for the CC session originated from C-nodes group I and at the same time as LS to develop a new CC session with the C-nodes of group II.

C-link: It is a link between a set of C-nodes and their corresponding LD.

Standby node: Those elements of MH path which do not act as CR-node are still used for route maintenance. Since they are not directly used in data communication, they are called standby node.

MH-CC routing is introduced in the following four steps:

4.3.1 Route Discovery

The goal of this step is to limit the number of potential CR-nodes. The best CR-nodes are those located along a straight line between source and destination. If the density of sensor nodes is high enough, standard MH routing protocols discover such nodes as the elements of the MH path. The effectiveness of the new approach to limit the searching domain is observed in figure 4.2.

In practice, the MH path might bend due to the lack of appropriate relay nodes or the existence of obstacles between source and destination. Such deviations degrade the quality of the CR-nodes. This effect is represented in figure 4.2. The node N_1 acts as the source. In the case of communicating to N_2 as the destination, the proposed approach select N_4 as CR-node which is an appropriate one because the relay nodes are almost located along the straight line between source and destination. However considering N_3 as the destination, N_5 would be the best CR-node whereas the proposed approach detects N_6 as the CR-node which is not an appropriate one. Nevertheless the proposed approach is still a feasible way to decrease the workload for searching of the CR-node.

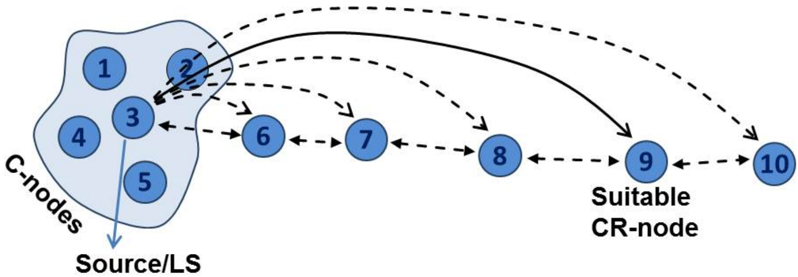


Figure 4.4: Route correction in MH-CC routing

4.3.2 Route Correction

The goal of this step is to develop C-links in forms of either CC-T or CC-R along the MH path. After the MH path is discovered, some of the attending nodes to the MH path are selected as CR-nodes. Route correction step is initiated from source and detects suitable C-nodes at its proximity as well as the optimum CR-node as LD. Similarly, the new CR-node acts as LS and detects the next CR-node based on its available C-nodes. This process is continued until the entire MH path is corrected.

The most challenging part of the route correction step is the detection of appropriate CR-nodes. As seen in figure 4.4, there are various possibilities ($N_6 - N_{10}$) to be considered as CR-node. However, depending on the CC characteristics including the number and the position of C-nodes, transmission channel quality and synchronization accuracy, only one of them is at the optimum distance. Other potential CR-nodes are rejected due to their inappropriate (short or long) distances. In this section it is assumed that the entire potential CR-nodes have the same capability and the only metric is their distance however, later we will present other effective metrics to select the optimum CR-node. In the following, one way to fulfill this task is presented.

- **Setting up of the C-nodes:**
  - Source/LS asks its neighbors to join as C-nodes for CC-T. In figure 4.4, there are four C-nodes (N_1, N_2, N_4 and N_5) around the source (N_3).
- **Detection of the Optimum LD**
  - The first node of the path which is between C-nodes and the destination (N_6 in figure 4.4) is considered as LD. It is a temporary LD and might be changed. Therefore its connection to the source

is represented with a dashed line.

  - C-nodes initiate OBCL synchronization by sending a *Synch.* message to the LD (N_6)
  - LD (N_6) evaluates the overall signal quality and sends a feedback to the source/LS via the existing MH path (Standby nodes).
  - Source/LS broadcasts the feedback to the entire C-nodes.
  - The iterations of OBCL are continued until the desired quality level is achieved.
  - If higher synchronization accuracy is still achievable (by continuing the iterations), current LD (N_6) asks its next relay node in MH path (N_7) if it can act as LD.
  - New LD (N_7) continues synchronization to receive the required signal quality.
  - If the required signal quality is achieved, a farther LD (N_8) is selected.
  - If before gaining the required quality, synchronization meats its maximum achievable accuracy, the new LD (N_{10}) refuses its task and the former LD (N_9) takes this responsibility.
  - CR-node is introduced to the C-nodes as well as its adjacent nodes in the MH path.

- **Scheduling of the Data communication and Acknowledgment**
  - An appropriate schedule is defined for data communication and acknowledgment. Due to the duality principle for data communication, phase compensation information achieved for CC-T is valid for CC-R as well. Therefore CC-T is applied to data communication and CC-R to acknowledgment.

- **Establishment of new C-link**
  - Current LD operates as a LS to establish a new C-link: it sets up a group of C-nodes and runs the procedure to find the next appropriate CR-node.

- **End of Route Correction**
  - Route correction procedure is continued until the entire path is modified.

At the end of the route correction step, a set of CR-nodes along the path between source and destination are detected which contact each other via two-sided C-links. In each C-link, a LS and its corresponding C-nodes directly contact a specific LD and receive its feedbacks through CC-R. Therefore, standby nodes are not used anymore.

4.3.3 Data Transmission

Beginning from source...

- Source/LS broadcasts its message to its corresponding C-nodes.
- The entire C-nodes including the source/LS apply appropriate phase shifts which are achieved in route correction step and wait for the transmission interval.
- C-nodes send their message simultaneously through their corresponding LD. The length of the message is set according to the duration of transmit mode. After that C-nodes switch to CC-R and wait for LD's feedback.
- LD receives the message and sends an acknowledgment back to the C-nodes directly via CC-R.
- The CR-node which contains the message (LD in previous C-link) acts as a LS for the next C-link.
- This procedure is continued until the message is delivered to the destination.

Referring to figure 4.4, node N_3 is responsible for contacting CR-node N_9. It shares the signal with its corresponding C-nodes (N_1, N_2, N_4, and N_5) and then all of them send the message through N_9 as their corresponding LD. Obviously, those of the CR-nodes which do not have adjacent C-nodes are unable to establish C-links. Therefore, they use the existing MH path to connect to the next node in MH path as a new CR-node.

MH-CC routing is summarized in table 4.1

4.3.4 Route Maintenance

At the first glance, MH-CC routing seems to be more vulnerable against dynamic situation and nodes' deactivation when compared to MH routing. It might be due to the extra *route correction* step or due to the need for the development of multiple CC sessions. However, it was proved in chapter 3 that using either MH or CC techniques to connect specific pair of source and destination, the same number of nodes are needed. Therefore the probability of nodes' failure or mobility for both methods is the same. However, the

Table 4.1: Summarization of MH-CC routing

Route discovery	
Standby Nodes	Discover a MH path between Source and destination
Route correction	
Beginning from source ...	
Source/LS	Broadcasts a request to its neighbors to set a C-nodes group
C-nodes	Response the request
Source/LS	Selects next node in MH path which is not C-node as the LD
C-nodes	Synchronize themselves based on current LD until demanded signal quality is achieved
Standby nodes	Carry messages of LD to C-nodes
LD	Asks its next hop if it receives the signal of C-nodes (even in low quality) as well. If so, it works as new LD
New LD	Continues synchronization. *If* demanded signal quality is achieved, It asks its next hop to carry out LD job. *Otherwise* It announces to the old LD that it is unable of being LD
LD	Announces the fixing of C-link to the C-nodes
LD	Sets certain schedule for CC modes
LS/Source	Broadcasts the schedule among the C-nodes
LD	Acts as a LS to establish the next C-link
This process continues until the entire path is corrected	
Data transmission	
Source/LS	Waits for the first transmission time slot to run CC-T
Source/LS	Shares its signal among its corresponding C-nodes
C-nodes	Relay the signal of the source after phase modification
LD	Receives the data and waits for the next CC-R time slot for acknowledgment
LD	Acts as a LS to send data over the next C-link

impact of the nodes' failure or mobility in MH and CC is not the same. The dynamic situation might lead to one of the following cases:

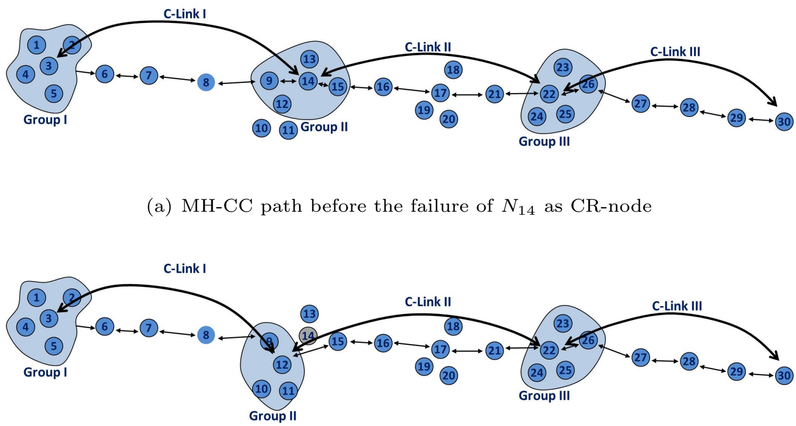
- **Failure or exclusion of a node:** The reason behind such problems might be the movement of sensor nodes, depletion, blockage or severe transmission channel effects. In MH, it results in the disconnection of source and destination while in case of CC, the C-link still works but with lower quality.
- **Small movement of one or a few of nodes:** As long as the adjacent relay nodes are in the coverage area of each other, such movements have no effect on the performance of MH routing. However, the phase synchronization of C-nodes is a determinant factor in the performance of CC. Due to the dependency of the carrier phase of C-nodes on their position, even small movements can have negative effects on the performance of CC although it might not lead to link breakage.

In other words in dynamic situations, CC shows higher reliability because its performance degrades smoothly. In case of MH, however, as long as the adjacent relay nodes are in the range of each other, the link is connected without any performance degradation. But as soon as one relay node fails or goes out of the coverage area of the other relay nodes, the link is disconnected. Therefore CC has a higher resistance against dynamic situation when compared to MH, although small changes (those which does not change the network topology) have negative effect on the performance in CC in terms of data communication. Consequently, MH-CC has a higher reliability than MH since in case of MH-CC the link between source and destination is composed of several CC sessions. The performance of MH-CC will be more accurately evaluated later in this chapter.

In this section, we address new challenges which might arise due to the new structure of MH-CC and propose appropriate solutions. In the entire solutions, the objective is to maintain the distributed structure of MH-CC. For this, CR-nodes are responsible for their corresponding C-links and C-nodes. Therefore, any problem in a specific C-link is solved by the CR-nodes at the beginning and the end of the C-link. In order to solve problems in C-links, it is worth noting that the solution should be with the least possible changes in the C-links. Because major changes in one C-link affect the other ones which increase the workload for re-establishment of CC sessions. Some of the major problems of MH-CC routing are listed below.

4.3.4.1 The Failure of a CR-node

It is the most severe problem which can happen in a MH-CC link. Depending on the role of the failed CR-node, the failure is detected in different ways.



(a) MH-CC path before the failure of N_{14} as CR-node

(b) MH-CC path after fixing the failure: N_{14} is substituted by N_{12}

Figure 4.5: Route maintenance in MH-CC routing when a CR-node is failed

- **Failure while acting as a LD:** The CR-node before it detects the failure because it does not receive any feedback.
- **Failure while acting as a LS:** The failed CR-node is detected by its corresponding C-nodes. Normally they expect to receive its message for transmission via CC-T.

The most cost-efficient solution for this failure is the substitution of the failed node with one of its corresponding C-nodes. However, if the failure is detected when the CR-node is working as a LD, there is no way for corresponding C-nodes to detect the problem. Thus standby nodes should report the failure to the C-nodes. Figure 4.5(a) shows a MH-CC connection composed of three C-links. In the case of the failure of node N_{14} as a CR-node, it should be substituted by either of N_9, N_{12}, N_{13}, or N_{15}. New CR-node has several tasks to fix the problem and retain the connection performance:

- The new CR-node updates the group of corresponding C-nodes. Because of its new position, the group of C-nodes is not necessarily the same as before. In figure 4.5(b), the MH-CC connection after correction is represented. As seen, the selection of node N_{12} as the new CR-node changes the list of the C-nodes to N_9, N_{10} and N_{11}.
- Considering the new CR-node as a LD, it contacts a group of C-nodes

in its previous C-link. These C-nodes (N_1, N_2, N_3, N_4, and N_5 in figure 4.5(b)) update their synchronization because of the different location of the new LD.

- As LS, new CR-node and its corresponding C-nodes update their synchronization with their corresponding LD (node N_{22} in figure 4.5(b).

The different position of the new CR-node might change the length of one or both of the C-links it belongs to as well as the number of C-nodes. For instance, in the WSN of figure 4.5, after fixing the problem, C-link I is shortened whereas C-link II is extended. In addition, substitution of the failed CR-node with one of its C-nodes degrades the number of C-nodes for the new CR-node which has negative effect on its C-link with the next CR-node (C-link II in figure 4.5). To compensate this degradation, new CR-node searches for new C-nodes. But if similar to figure 4.5(b), there is no possibility to add new C-nodes, the degradation should be compensated by increasing the synchronization accuracy. Therefore, it is highly recommended that the maximum capacity of the synchronization is not used during route correction step. Then, in the case of such failures, C-nodes run further iterations to compensate the power leakage due to the extended C-links or decreasing of the number of C-nodes.

4.3.4.2 C-node Failure

This failure directly affects the power level at the destination. If the C-node is failed during CC-R, its corresponding CR-node detects the failure. But in the case of CC-T, the next CR-node detects the failure and reports it to the CR-node whose C-node is failed.

One solution would be to find a new C-node to substitute. If there is no one, similar to the first problem, the decreased power level due to the lack of a C-node is compensated by improving the synchronization accuracy. If the synchronization is in its highest accuracy level, fixing this problem leads to the modification of the next C-links which is so resource demanding. More accurately:

- The C-link after the failed C-node should be shortened. For this, a closer CR-node is selected instead of the one which works as LD for the group of C-nodes with one failed node
- Synchronization is updated based on the new LD
- Corresponding C-nodes to the new CR-node are updated, they renew their synchronization and in the case of low power level at their corresponding LD, this modification is spread to the entire link.

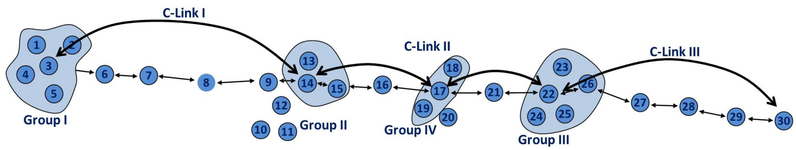


Figure 4.6: The proposed solution of C-node failure problem

For instance, if in figure 4.5(a) node N_{13} is failed, node N_{17} is asked to act as a CR-node by developing its C-nodes group and compensating the decreased transmission range of group II. N_{17} initializes its C-link to the next CR-node N_{22}. This solution efficiently avoids the need of modification of other links. Due to the shorter distance in the new C-links, some of the C-nodes in groups II and III can be deactivated. The new MH-CC path is represented in figure 4.6.

4.3.4.3 The Failure of a Standby Node

The standby nodes are only used to report the failure of a CR-node when it works as a LD. Therefore their failure has no effect on the data communication over MH-CC links. This failure is detected by adjacent standby nodes. Without any interruption in the data communication, standby nodes find another one as substitution. This process is similar to the route recovery in standard MH routing.

4.3.4.4 The Mobility of C-nodes or CR-nodes

The failure of CR- or C-nodes is addressed before. However, there are situations in which these nodes are not failed but slightly change their position which would disturb the synchronization accuracy. In such cases, the corresponding C-link is connected but with lower performance. This problem is detected by the CR-nodes in LD mode because they receive lower power and the problem can be solved by updating CR-nodes' synchronization.

Based on the route maintenance issues as well as their corresponding solutions mentioned in this section, an efficient way to increase the robustness and reliability of MH-CC based links would be to avoid the use of the maximum potential capabilities of C-links in terms of the number of C-nodes and the synchronization accuracy.

4.4 Desired Characteristics of Routing in MH-CC

As seen in the previous section, MH-CC is a framework which enables existing routing protocols to integrate to CC. In this section, those of routing protocols better matching to MH-CC approach are discussed.

4.4.0.5 Re/Proactivity

CC can be integrated to either reactive or proactive protocols. However, due to the complexity of MH-CC paths, reactive protocols suit more because new paths are developed only on-demand. Although reactive approaches decrease the data delivery rate, higher speed of MH-CC in comparison to MH routing techniques solves this problem.

4.4.0.6 Route Discovery Approach

MH-CC is compatible with both distance vector and link state based routing protocols. However, later in this chapter, multi-metric MH-CC is introduced to improve the performance of MH-CC routing which suits more distance vector routing.

4.4.0.7 Network Structure

Either of flat or hierarchical structures can be applied to MH-CC. In flat networks, the realization of MH-CC is much more complex because of the higher degree of freedom to select C-nodes and CR-nodes. However, in hierarchical networks, nodes designating to a cluster collaborate together and cluster-heads act as CR-nodes. Therefore most of the roles are defined in advance. In this chapter, as a general case we focus on flat networks.

4.4.0.8 Location Awareness

There are three different levels of location awareness:

- No information about the position and relation (list of neighbors) of the nodes is available
- Nodes are only aware of the list of their neighbors
- Nodes are aware of their absolute locations

The idea of MH-CC is applicable to the last two categories. However, the focus of this chapter is mostly on the second case (relative information) as it is more common in WSNs.

4.5 Performance Evaluation of the Routing Approach

Various network simulator software packages such as NS-3[1], OMNET++[2] (MIXIM and Castalia packages) as well as OPNET[3] can be applied to simulate WSN's algorithms and protocols. At the beginning of this research, a study has been performed to find suitable network simulator for simulation and performance evaluation of MH-CC. An appropriate simulator for this research should be able to simulate:

- Routing approaches, as well as physical layer techniques in detail (route discovery, multi-metric routing, signal modulation, carrier phase, synchronization and etc.),
- Transmission range extension due to CC,
- Computational load and energy consumption.

Although some of the existing software packages allow the user to develop new sensor node's modules to extend or customize their capabilities, none of them satisfy the required objectives of this research completely. Therefore, a specific Matlab toolbox to simulate MH-CC is developed. This toolbox includes sensor nodes characteristics such as battery storage, mobility mode, modulation type, transmission power level as well as WSN's characteristics like the distribution of the nodes, density and the number of sensor nodes, the length of different (routing and data) messages, transmission channel effects and data communication method (multi-hop or MH-CC).

4.5.1 Optimum Level of Synchronization Quality

The overall transmission range of C-nodes is a function of transmission range of the individual nodes, required quality level (BER or SNR) at the receiver, synchronization accuracy, and the number of C-nodes. The first parameter depends on the characteristics of the sensor nodes and has a linear effect on the overall collaborative transmission range. The second one is defined based on certain application scenarios. In other word, the first two factors can be considered as constant values and the overall transmission range of C-nodes

[1] www.nsnam.org
[2] www.omnetpp.org
[3] www.opnet.com

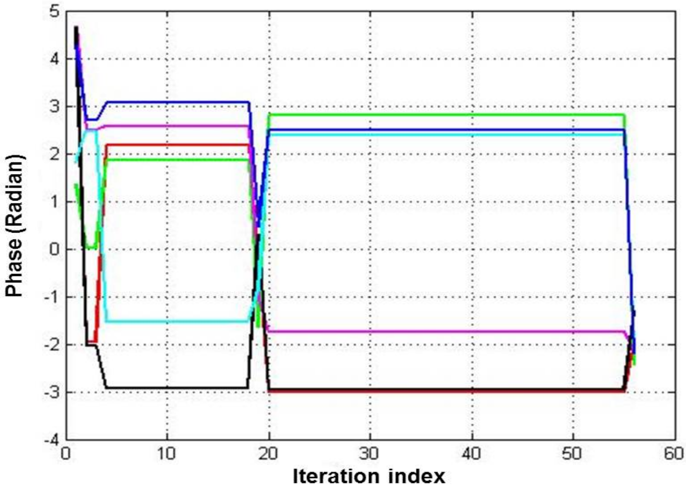
is a function of the synchronization accuracy and the number of C-nodes. Therefore, in order to gain a certain quality level at the destination there are various possible levels of synchronization accuracy and number of C-nodes. The goal of this section is to find the optimum setting of these two parameters when different levels of signal quality at the destination are considered.

For this, the behavior of OBCL-based synchronization technique is considered in detail. We have considered a CC session composed of a group of M C-nodes and a remote destination. A LoS transmission channel with free space path loss and the same noise level for the entire C-nodes are considered. Other parameters like the distribution of C-nodes, distance between the C-nodes and destination or the length of *Synch.* message have no role in our analysis.

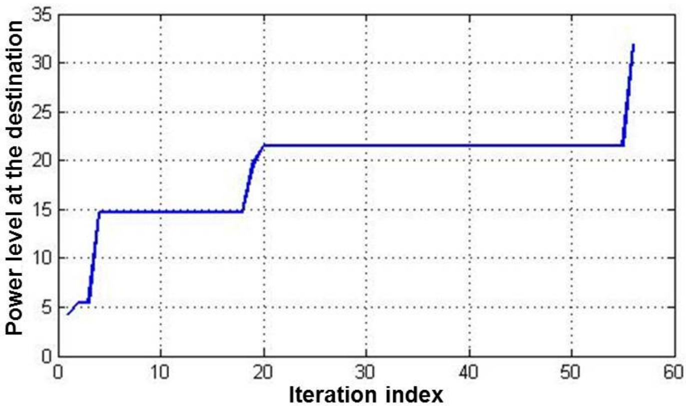
Figure 4.7(a) shows the behavior of the carrier phase of $M = 6$ individual C-nodes over the OBCL iterations. X-axis represents the number of iterations and Y-axis is the phase (in radian) of the C-nodes signals at the destination. As seen, the variation of carrier phases is discrete. It is due to the OBCL procedure to synchronize C-nodes. Although the carrier phase of C-nodes varies randomly at each iteration, only those phases having positive effects on the overall power level at the destination are maintained.

The corresponding power improvement pattern at the destination is represented in figure 4.7(b). As seen, at each jump in carrier phases, power level improves as well. However, the power improvement pattern highly depends on the carrier phases which vary randomly. Therefore judging about power improvement pattern based on one or a few samples is not realistic. Therefore, in another simulation we have repeated this simulation over 1000 times and the results are averaged to remove the effects of random phase modifications. In addition, different number of C-nodes, $4 < M < 12$, are considered. It enables us to compare the behavior of OBCL for different number of C-nodes. However, power level at the destination is not suitable for this goal because it depends on M. Therefore we define *synchronization efficiency* as the ratio of the power level at the current synchronization accuracy and the maximum achievable power level in case of perfect synchronization. This parameter varies between 0 to 100% and is independent of M. In addition, an ideal transmission channel (without multi-path effect) with free space path loss and constant noise level among C-nodes and destination is considered. This assumption does not limit the generality of the simulations because it does not affect the evaluation metrics and has no negative impact on the analysis.

The results are represented in figure 4.8. The curves represent the relationship between synchronization efficiency (Y-axis) and the number of iterations (X-axis) for different number of C-nodes. Focusing on a specific value of M, it can be said that the synchronization efficiency improves by increasing the number of iterations. However, the improvement rate decreases by increasing



(a) Phase modification pattern of $M = 6$ C-nodes



(b) Pattern of power level improvement at the destination

Figure 4.7: The behavior of phase and output power at OBCL synchronization technique

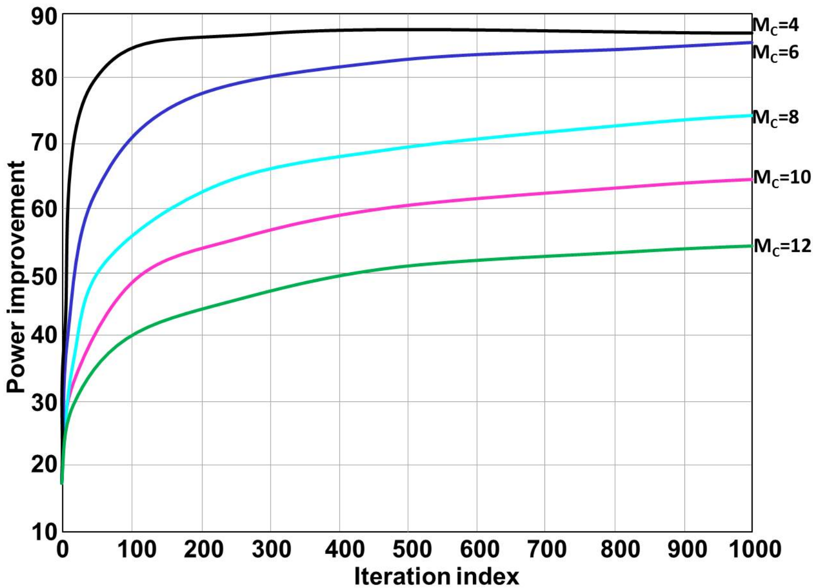


Figure 4.8: Illustration of the OBCL synchronization efficiency for different values of M

the number of iterations. As a numerical example, in case of $M = 6$, the synchronization efficiency improves very fast during the first 100 iterations so that it reaches to 71% whereas the improvement during the second and third 100 iterations are 8% and 3% respectively. However, the energy consumption of each iteration is fixed and depends only on M and the transmission power level. Thus the cost of a specific improvement in the synchronization efficiency and equivalently power level at the receiver is not the same and increases over iterations. Therefore depending on the application scenario, there exists an optimum value for synchronization efficiency.

In addition the improvement rate of synchronization efficiency is not fixed for different values of M and decreases by increasing M. In other words, for higher values of M, the synchronization efficiency is saturated at higher iterations. The reason is that by increasing M the domain through which the C-nodes select a set of phase shifts extends. This decreases the probability of selecting a constructive set of phase shifts. Therefore, a specific improvement in the synchronization efficiency is achieved after higher number of iterations. As the result of this analysis, it can be said that to gain a specific power level at the destination, CC is started with an initial value of M. But the synchronization efficiency should be checked regularly. If OBCL is not reasonable any more, a new C-node should join CC. Now the synchronization efficiency follows another curve and makes the continuation of OBCL reasonable. The adding of C-nodes and continuing of iterations is repeated until the required power level at the destination is achieved.

4.5.2 Optimum Setting of MH-CC in Terms of Energy Efficiency

In MH-CC, a path between specific source and destination is composed of several CC sessions. The setting of MH-CC includes the number of C-nodes as well as the synchronization accuracy at each CC session. To find the optimum number of C-nodes and synchronization accuracy, the cost of each iteration as well as the achievable power level with certain synchronization accuracy should be calculated. For this, it is assumed that during synchronization, C-nodes send the signal $S_i^{synch}(t), 1 < i < M$ with energy E_{tr} to the destination. Assuming the same data transmission characteristics at C-nodes and destination, each iteration includes $M + 1$ interactions which costs

$$E_{it} = (M + 1).E_{tr} \tag{4.1}$$

On the other hand, the received power at the destination is

$$P_{rec} = \alpha L_{chan} \cdot M_C^2 P_{tr} \tag{4.2}$$

Table 4.2: The cost of CC in terms of energy consumption for different settings

α	$M = 4$	M=6	$M = 8$	$M = 10$	$M = 12$
10%	1.6	3.6	6.4	**10**	**14.4**
20%	3.2	7.2	**12.8**	20	28.8
30%	4.8	**10.8**	19.2	30	43.2
40%	6.4	14.4	25.6	40	57.6
50%	8	18	32	50	72
60%	9.6	21.6	38.4	60	86.4
70%	**11.2**	25.2	44.8	70	
80%	12.8	28.8	51.2		

Table 4.3: Achievable power level during CC corresponds to the settings of table 4.2

α	$M = 4$	$M = 6$	$M = 8$	$M = 10$	$M = 12$
10%	5	12	16	**20**	**24**
20%	5	12	**16**	40	72
30%	5	**24**	56	120	264
40%	10	42	152	350	1200
50%	20	108	432	1170	4920
60%	45	258	1272	5650	59916
70%	**75**	570	4632	44640	
80%	180	1650	27768		

where α is the synchronization efficiency. L_{chan} is the transmission loss between C-nodes and destination. It depends on the carrier frequency of the communicating signal and distance between transmitter and receiver. Therefore since our analyses are related to a specific set of C-nodes and destination, this parameter is fixed. Due to the constant values of P_{tr} and E_{tr} depending only on the nodes' structure, E_{it} and P_{rec} are modified as functions of α and M.

For further investigations, $4 < M < 12$ C-nodes are considered. The entire nodes have an equal amount of energy storage. In addition, energy consumption during each OBCL iteration is the same. OBCL continues until various synchronization efficiency levels $10\% < \alpha < 80\%$ is achieved. The results of this analysis including the achievable power level at the destination as well as the number of iterations are presented respectively in tables 4.2 and 4.3. Since at each iteration a constant amount of energy is consumed, the number of iterations would completely represent the energy consumption.

This table shows that to gain a certain power level at the destination, using the maximum possible number of C-nodes is the most energy efficient way. For instance, to achieve $P_{rec} \approx 10mW$ at the destination, different possibilities can be considered which are marked in the table. Corresponding options to relatively small set of C-nodes ($M = 4$, 6 and 8) show that regarding the improvement of the synchronization, using higher number of C-nodes is more efficient. The reason is that for small values of M, α is located in or so close to saturation area. But by increasing M, the required power level is achieved with lower values of α far from the saturation area. However, this pattern is not continued for the last two cases. The reason is the decreasing of the increment rate of α over the number of iterations when higher values of M are considered. As discussed before in figure 4.8, by increasing both α and M, the improvement rate of the synchronization efficiency decreases considerably.

Based on the setting of this simulation scenario, the best synchronization efficiency in terms of energy consumption is between 20% and 40%. Further simulations with various settings confirm this optimal range. The reason is that synchronization efficiency improves faster at the first iterations. However, as discussed before, the improvement rate of synchronization efficiency decreases by increasing M. So, it would be more energy efficient if relatively low values of synchronization efficiency are selected. On the other hand, low synchronization efficiency decreases the overall energy which is received by the destination. The only way to compensate this energy leakage is to increase M. Although increasing M increases the power level at destination, the synchronization efficiency has a lower improvement rate for higher values of M.

4.5.3 Reliability Analysis

In the last section, it was shown that the application of the maximum number of C-nodes and $20-40\%$ synchronization efficiency would lead to the minimum energy consumption in MH-CC. In this section, the suitable MH-CC setting to gain high reliability is investigated. Reliability is defined as the delivery rate, R_D, which is calculated as the percentage of the communicated messages successfully delivered in a certain time interval.

The simulation scenario is presented in figure 4.9. A two dimensional WSNs in which $M_T = 100$ sensor nodes are randomly distributed with uniform distribution in a $100 \times 100m^2$ area is considered. The transmission range of the individual nodes is 20 m. Sensor nodes can be either fixed or mobile with random speeds and directions and straight paths, however they can move only at the end of each time slot. So, routes are valid during each time slot. In addition, the entire nodes have the same RF and antenna structure as well as transmission power level. At the beginning, the entire nodes have the same battery storage. For each time slot, source and destination are

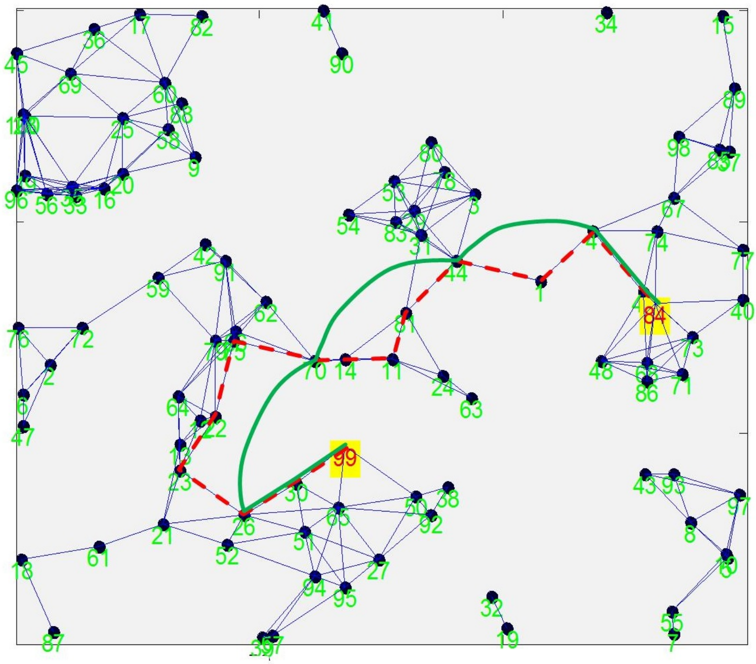


Figure 4.9: Scenario considered to analyze reliability and energy efficiency

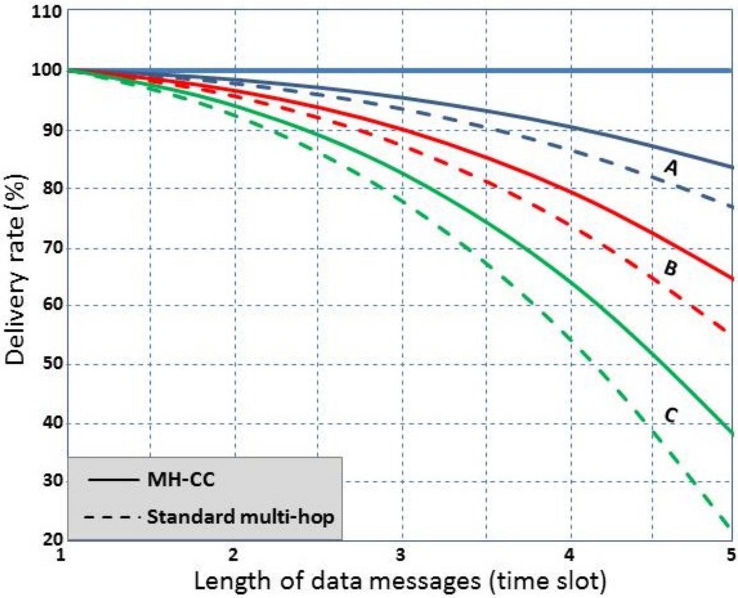


Figure 4.10: The impact of MH-CC on the reliability for different lengths of messages and mobility modes

selected randomly. Both MH and MH-CC routing are used to set a path for data communication. Route discovery is performed on-demand (a reactive approach) and OBCL technique is applied to phase synchronization. Routing packets are much shorter than the length of data messages. In this simulation, it is assumed that $T_r = 0.1T_d$, where T_r and T_d are the length of routing and data messages. A threshold is considered for the length of MH path to avoid severe energy waste in the cases that source and destination are selected in separated parts of the network. Since the first step in MH-CC routing is to discover a MH path, this problem has the same impact on MH and MH-CC routings.

Four different mobility modes $A-D$ are considered. At the end of each time slot, a random number of sensor nodes are selected to change their position. The mobile nodes move on straight lines with random directions (uniform in $(0, 2\pi)$) and random speed in the range $(0 \quad V)$ where V is equal to $0, 10, 20$ and $30m/s$ for modes $A-D$, respectively. The test is performed for different message lengths as well because both nodes' mobility and message length affect the reliability.

Figure 4.10 represents the delivery rate of both MH and MH-CC approaches for different length of data messages and mobility modes. It shows that in case of no mobility (mode A), regardless of the length of the message, $R_D =$ 100% for both MH and MH-CC approaches can be achieved. However, R_D decreases for higher mobility modes or message lengths. In a certain mobility mode, R_D decreases by the increasing message length with a rate of more than linear. The reason is that for long messages, a path between a certain source and destination is used for a longer time. Therefore the probability of the movement of the attending nodes increases. Increase in the mobility speed of the nodes increases this probability as well. Therefore, corresponding curves to the higher mobility modes represents lower data delivery rate and reliability.

Another interesting result of this simulation is the difference between the corresponding curves of MH-CC and standard MH. In comparison, MH-CC shows higher resistance against mobility and message length. It is due to the following reasons:

- Paths between certain pairs of source and destination are composed of fewer relays in MH-CC
- MH-CC is faster due to its less relays
- Exclusion of even a few nodes does not disconnect the MH-CC links whereas it causes link-breakage in MH paths

So, MH-CC is more robust in the case of dynamic situation.

4.6 Multi-Metric MH-CC

In the previous sections, specific settings to gain different levels of reliability and energy efficiency in MH-CC are extracted. However, what is still missing is the way based of which sensor nodes autonomously switch to different settings. As a solution, we focus on the application of multi-metric approach in MH-CC.

Multi-metric routing is not a new topic and is widely used in MH routing for establishing a more realistic cost function for the calculation of the cost of different links. For instance, in case of significant noise and fading, the transmission channel degrades the signal quality. If the number of hops is considered to estimate the cost of each path, although shortest paths are selected, due to the severe channel effects, it would not be necessarily the best choice. However, if in each path the state of the links of the path are applied to calculate the overall cost of the path, more realistic results can be achieved [BB12] [BBM12]. Multi-metric idea can be applied to MH-CC in different forms which are discussed in this section.

4.6.1 Multi-Metric Approach to Discover MH Path

The first option would be in route discovery step to find a MH path between source and destination. Sensor nodes attending to the MH path are selected as the potential CR-nodes. Therefore their quality directly affects the performance of MH-CC.

Different metrics including hop count, environmental noise and channel state, battery storage level, and relay or processing load might be considered to represent the capability of the nodes to join MH path. Depending on the application scenario and network objectives, specific metrics with certain weights are defined in advance. Sensor nodes evaluate their overall grades by the weighted combination of their grades in the individual metrics. These grades are considered to represent the capability of the sensor nodes to participate in routing.

4.6.2 Multi-Metric Approach to Select CR-Node

After the MH path is discovered, a multi-metric approach can be applied as well to select the suitable CR-nodes. There are different factors which might affect the capability of a CR-node: network objectives specifically the desired energy efficiency and delivery rate, the number of available C-nodes, the length of C-link when it acts as LD, battery storage level and relay or processing load. Therefore, in the case of multi-metric MH-CC, each potential CR-node estimates its grade. After the farthest CR-node is detected, the entire potential ones send their grade to their previous source/LS (which coordinates the establishment of the C-link) to select the optimum CR-node.

4.6.3 Multi-Metric Approach to Select C-nodes

Multi-metric approach can also be applied to select C-nodes. This approach is discussed in chapter 3 and can be directly utilized in MH-CC. As mention before, source/LS sends a request to its neighbors together with a threshold level. The adjacent nodes estimate their overall rank and participate in the CC session only if their ranks are higher than the threshold. Since this threshold is iteratively set based on the interaction between source/LS and LD, the minimum number of highest-ranked nodes are selected for CC session.

4.7 Summary

In this chapter, the novel CC+ technique introduced in chapter 3 is integrated to multi-hop networks. The algorithm proposed in this chapter is in fact a general platform which is applicable to a wide range of routing protocols. Standard multi-hop routing protocols are usually realized in two steps: route discovery and data communication. The newly proposed MH-CC approach adds a new step after route discovery which is dubbed route correction. In this step, the multi-hop path is investigated to find out those parts which are suitable to be connected via CC. In the resulting path, the source is connected to the destination via multiple C-links (CC-based connections). Therefore, in comparison to the standard multi-hop, the path between specific source and destination is composed of fewer relays. The performed analyses in this chapter show that MH-CC has a potentially higher reliability which is, however, at the expense of a slight increase in the energy consumption to organize the CC sessions. Finally, in order to match MH-CC to the dynamic situation of WSNs, a multi-metric approach is utilized to relate the MH-CC reliability factor to specific parameters, e.g. data generation rate.

Chapter 5

Collaborative Communication in Mobile WSNs

The application of mobile nodes in WSNs (MWSN) [RJW+07] is an efficient networking technique which suits resource-restricted sensor nodes well. In MWSN, the mobile nodes move inside the sensing field and aggregate the data of sensor nodes. Sensor nodes search for mobile nodes at their proximity by listening to the channel and as soon as a mobile node is detected, they send their data. Due to the relatively simple tasks of sensor nodes, MWSN matches to resource-restricted WSNs reasonably well although the deployment and maintenance of mobile nodes might be challenging. However, similar to the other data communication and networking approaches in WSNs, MWSNs suffer from low reliability and flexibility. In order to solve this problem, CC is integrated into these networks as CC-MWSN.

The major objective of CC-MWSN is to improve the network connectivity and data aggregation rate without changing the number or mobility pattern of mobile nodes as well as the transmission range and density of the sensor nodes. For this, sensor nodes are grouped and programmed to run a specific type of CC in both receive and transmit modes. Sensor nodes use CC-R to find the direction of the mobile node at their proximity and CC-T for data communication. The optimum setting for an experimental scenario is then extracted.

The ideas and analyses results of this chapter are partially published in [FBZB13]:

- Energy-efficient collaborative data collection in mobile wireless sensor networks, CISS'2013

5.1 Problem Statement

The principle of MWSNs was reviewed in chapter 2. In this chapter a certain type of MWSNs is considered in which Mobile nodes aggregate the data of sensor nodes and deliver them to a central base station. This type of MWSNs perfectly matches to extended WSN applications e.g. to cover a mega-city in which millions of sensor nodes are deployed. The problem is that especially for relatively long term scenarios, the application of mobile nodes would be quite resource demanding. As an alternative, the existing mobile objects in the network area would act as mobile nodes by carrying transceivers. For instance in urban sensing applications, Taxis can do this task as they move all around the city. Although their mobility pattern is unpredictable, they are always preferred due to their cost efficiency.

The urban sensing network in Beijing city is a good example of such networks. Sensor nodes are uniformly distributed in Beijing city and grouped into clusters. Taxis, as one of the major types of public transportation systems in this city, are acting as mobile nodes to collect data from the static road-side sensor nodes. The major problem of this network is the mobility pattern of the Taxis. They mostly move along the main streets, therefore sensor nodes located in such areas meet the mobile nodes very often, whereas those installed far from main streets might suffer from long term delays. On the other hand, the concentration of the Taxis is mostly in the city center, therefore especially in sub-urban areas, some sensor nodes might rarely meet mobile nodes (even after some days). Since sensor nodes do not have adequate memory, their data is overwritten several times.

Figure 5.1 shows the heat-map of data collection by 5000 Taxis in a period of 2 hours (from 8 AM to 10 AM on May.1st, 2009) in Beijing city. The color of each point indicates the number of sensor nodes at the corresponding location whose data is collected. As is shown, sensor nodes in the city center and near the main roads are more likely to be visited and get their data collected, while *cold spots* exist in suburbs and large parks where data can hardly be collected. Statistics show that data collection percentage is lower than 50%.

The data collection in Beijing city MWSN is more investigated in figure 5.2. This figure presents the percentage of the sensor nodes whose data is being collected by different numbers of the Taxis in 24 hours. As seen, even increasing the number of Taxis cannot efficiently improve the coverage area. The improvement rate of data collection approaches to zero by increasing the number of Taxis, so that an increase of 3000 to 5000 in the number of Taxis leads to only 7% improvement in the coverage area. The reason is the low probability of Taxis passing through certain areas such as large Parks or suburb areas.

The Beijing Taxi trajectory database contains 30-day GPS records of $27,848$ Taxis traveling in an area of 841 km^2 within 39.759°N to 40.023°N latitude and 116.209°E to 116.544°E longitude, which is approximately the area within the fifth-ring road in Beijing. The following experiments are conducted using the real traces of Taxis on May 1, 2009 after invalid traces being removed. The sensor nodes' data communication characteristics are:

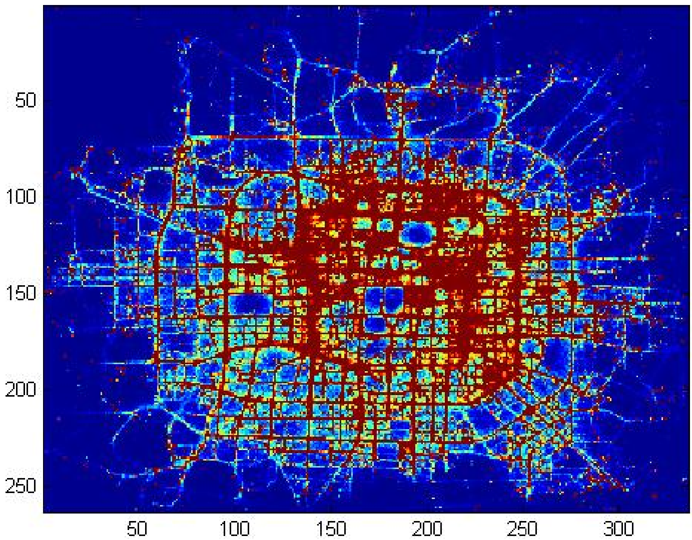


Figure 5.1: Data collection pattern in Beijing performed by 5000 within 2 hours

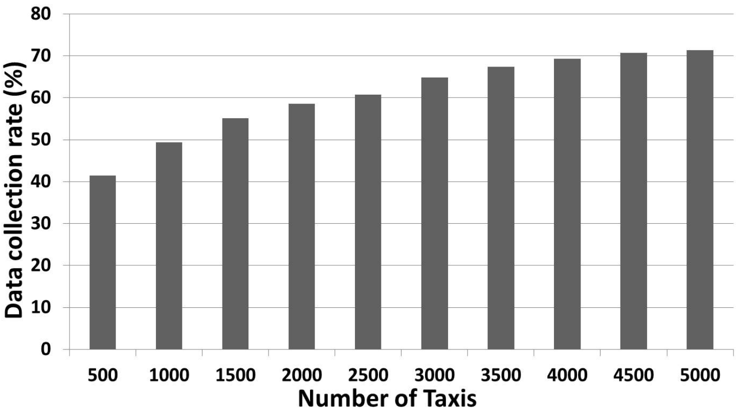


Figure 5.2: Data collection percentage in Beijing city for different numbers of Taxis

Noise level:	$N_0 = -171dBm$
Antennas' transmission and reception gain:	$G_t = G_r = 2dBi$
Carrier frequency:	$f = 2.4GHz$
Bandwidth:	$B = 10K$
Sensor nodes Pick to Average Ratio (PAR):	$\xi = 2$
Modulation type:	QPSK
time needed to deliver messages to mobile nodes:	$T_m = 0.1ms$
Nominal transmission range:	$d_0 = 100m$
Path loss factor in local transmission:	$k = 3.5$

5.2 Solution: Application of Collaborative Communication in MWSN

Through extending transmission range of sensor nodes, CC can efficiently increase the percentage of sensor nodes whose data is collected. As illustrated in figure 5.3, to achieve this, sensor nodes:

- are grouped into clusters,
- use CC-R at each group to search for mobile nodes in a wider area around themselves compared to their transmission range,
- maintain their corresponding phase shifts as soon as a mobile node is detected,
- run CC-T based on their phase shifts and deliver their data to the mobile node.

Provided that in comparison to the speed of mobile nodes, sensor nodes are fast enough to establish CC-T, the data is delivered to the mobile nodes because the movement of mobile nodes is negligible. Therefore, CC-MWSN idea can efficiently increase the network connectivity without the need for increasing the transmission range of the individual nodes. However, in order to realize this idea, the following challenges and requirements should be addressed:

- **Lack of Remote Node for Synchronization:** In the entire synchronization approaches mentioned in chapter 2, C-nodes interact with a remote node (destination in CC-T or source in CC-R) to set their carrier phases. However in CC-MWSNs, C-nodes utilize CC first to search for the mobile nodes at their proximity. Therefore mobile nodes are not appropriate options to be used for the synchronization of C-nodes. Moreover, due to their random movement, they might approach the C-nodes from different directions. Thus, the synchronization setting

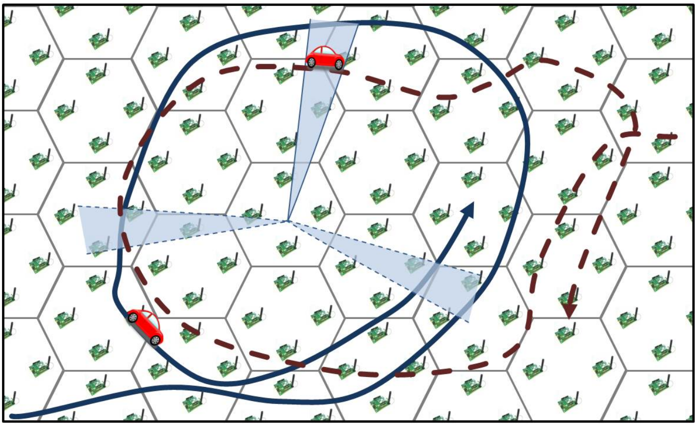


Figure 5.3: Sensor nodes at each cluster use CC-R to detect a mobile node and then use CC-T for data communication

is valid only for one data collection session. In addition, sensor nodes are not capable of running complex tasks needed for almost all of the previously mentioned synchronization approaches.

- **Directive Pattern of CC:** In standard MWSN, sensor nodes listen to the channel to detect a mobile node at their transmission range. Due to the omni-directional pattern of the sensor nodes, regardless of the direction from which a mobile node is approaching, sensor nodes send their data soon after they detect a mobile node at their proximity. However since the collaborative pattern of sensor nodes is directive, the same approach cannot be applied for CC-MWSN. The entire directions need to be scanned to detect the approaching mobile nodes.
- **Suitable Transmission Range:** According to CC, the transmission range varies as a function of the number of C-nodes (sensor nodes per cluster). Although collaborating with higher number of C-nodes would lead to higher transmission range, it consumes more energy. Therefore, depending on the mobility pattern and the number of mobile nodes as well as the distribution of the sensor nodes and the desired network connectivity rate, there is an optimum value for transmission range extension which should be extracted.

5.3 CC-MWSN Algorithm

Similar to the standard data collection approaches in MWSN, CC-MWSN is composed of three steps: initialization, scanning and data communication. However because of the application of CC, these steps are performed in different ways. In the following, CC-MWSN is explained in detail:

5.3.1 Initialization

At the initialization step, sensor nodes are deployed in clusters so that the entire nodes of a cluster can directly contact each other and the coordinator turns around the nodes to regulate the workload. Depending on their positions in the array, each sensor node has a list of phase shifts. If the entire nodes of the array utilize e.g. their i-th phase shifts to either CC-T or CC-R, they will demonstrate their expected transmission or reception capability in the corresponding direction. The coordinator is responsible for the decision and announcement of the operating direction.

5.3.2 Scanning

This step is initialized when one of the sensor nodes has some data to deliver. This node, which is considered as the coordinator, broadcasts a *Scanning* request to the other members of the cluster to listen to the channel. The request includes also the index of the scanning direction. Sensor nodes simultaneously listen to the channel based on a predefined schedule. They apply their corresponding phase shifts to the signals which they have received and then send the signals to the coordinator. The coordinator receives the combination of the signals which would be the signal of a certain direction. By changing the phase shifts, the entire directions are scanned. This process is repeated until a mobile node is detected. The phase shifts are then maintained as the corresponding phase shifts to the direction of mobile node.

5.3.3 Data Transmission

Provided that sensor nodes are fast enough to detect the direction of the mobile nodes, the direction would be valid for data transmission. On the other hand, according to the reciprocity theorem in communication, the corresponding phase shifts to the mobile node's direction can be utilized in CC-T to extend the transmission range to the same direction. Therefore, acting as a source, the coordinator broadcasts its data and the C-nodes relay it to the mobile node after they apply their phase shifts.

Table 5.1 summarizes the CC-MWSN data collection algorithm.

Table 5.1: CC-MWSN steps

Initialization	
Sensor nodes	Are deployed in clusters with appropriate list of phase shifts
Scanning	
C-nodes	One which has data for transmission acts as coordinator
Coordinator	Broadcasts a scanning request with a specific direction index
C-nodes	Receive the impinging signal in a certain period
C-nodes	Send their signals simultaneously through the coordinator after the application of appropriate phase shifts
	If a mobile node is detected
C-nodes	Maintain the last set of phase shifts as the corresponding phase shifts to a mobile node
	Otherwise
Coordinator	Sets another direction
C-nodes	Repeat the scanning step for new direction
Data Communication	
Coordinator	Broadcasts the sensing data
C-nodes	Set their carrier phases based on the corresponding phase shifts to the target direction
C-nodes	Send the data simultaneously through the mobile node

5.4 Appropriate CC Approach to Apply to CC-MWSN

The appropriate CC approach should be based on the minimum possible workload for sensor nodes and can be realized without a remote node. Since sensor nodes are manually deployed and are static, proper phase shifts can be estimated in advance based on their predefined positions and loaded to the sensor nodes. According to the beamforming theory [Tre02], the arrangement of the C-nodes plays a key role in the performance of CC in both receive and transmit modes. On the other hand, the direction from which mobile node might approach is random. Therefore, sensor nodes of a cluster should be able to work in the entire directions. For this, circular arrangement would be the best.

The performance of an array antenna in terms of transmission range extension is represented by array factor (AF). According to [Tre02], for a circular uniform array composed of M isotropic antennas, array factor is calculated as:

$$AF(\theta, \phi) = \sum_{n=1}^{M} a_n e^{jkrSin(\theta)Cos(\phi - \phi_n)} \tag{5.1}$$

where a_n and ϕ_n are the excitation and the azimuth angle of n-th element, r is the radius of the array and $k = 2\pi/\lambda$. Since the transmission range of the array ($max(AF)$) varies as a function of M and r, before deployment of the sensor nodes, optimum values of these parameters should be estimated. For this, in the next section appropriate model to estimate optimum transmission range is derived.

5.5 Optimal Transmission Range (OTR)

It is assumed that M static sensor nodes with transmission range of r_T are randomly distributed in the sensing field and are grouped in N clusters. Each cluster is composed of M_C nodes and has a diameter of $d_0 = 2r$ (or equivalently, the maximum distance between any pair of nodes in a cluster is d_0).

A sensor node is considered *collected* when its data is successfully transmitted to a mobile node. Note that for *collection*, the period in which a specific sensor node is connected to a mobile node should be long enough. It is quit probable that a mobile node is in the communication range of the sensor nodes for only a short period of time, which is not enough for data transmission. The network connectivity (P_C) is defined as the probability of all the sensors being collected by the mobile nodes at least once within the time constraint

T_{MAX} and the network is considered as connected if this probability is larger than a threshold value, C. Mathematically:

$$P_C = P\{\bigcap_{i=1}^{M} A_i\} > C, \tag{5.2}$$

where A_i is the event that node i is collected at least once by the mobile nodes within T_{MAX}. It can also be said that the network is functional if the probability of each sensor node being visited by the mobile nodes at least once within T_{MAX} is larger than C. This definition is due to the fact that in most WSN applications, only one sample of a sensor node in a certain period of time is needed to reconstruct the sensing field. In the meantime, data from a certain percentage of sensor nodes (determined by C) should be sufficient to get the full view of the field. Therefore, C represents somehow the desired accuracy or the number of sensor nodes in the unit area whose data is needed to have a complete view of the field. In practice, the percentage of the collected nodes is utilized to calculate the connectivity.

The Optimal Transmission Range (OTR) is defined as the minimum communication range that satisfies $P_C > C$. That is,

$$OTR = \min_{P_C > C} R_{CC} \tag{5.3}$$

where R_{CC} is the transmission range of sensor nodes during collaboration. Given OTR for a certain scenario, we can always derive the optimal energy consumption.Therefore, in the following section, we will further discuss the OTR under different mobility models.

5.5.1 OTR for Random Walk Mobility Model

In this mobility model, N_m mobile nodes perform random walk on the unit disk, resulting in a uniform location distribution at each time slot. It is assumed that the independent movements are performed at the end of each time slot. Therefore, during the time slot, the mobile nodes are fixed.

5.5.1.1 OTR for one cluster ($N = 1$)

Suppose there is only one cluster of M_C sensor nodes deployed on the unit disk. During CC, sensor nodes construct a beam-pattern of $\theta \in [0, 2\pi]$ with the transmission range of $R_{CC} = M_C \cdot r_T$ and beam-width of $\Delta\theta$. Therefore the probability of the detection of one mobile node in the coverage area of the C-nodes is

$$P(1,1) = \frac{\Delta\theta\pi R_{CC}^2/2\pi}{\pi R^2} \tag{5.4}$$

where $P(n,m)$ is the probability of the detection of one mobile node out of m in one of the n existing clusters (here $m = n = 1$) and R is the radius of the area the sensor nodes are deployed on, and is set to 1 meter. Therefore,

$$P(1,1) = \frac{\Delta\theta R_{CC}^2}{2\pi} \tag{5.5}$$

So the probability of the sensor nodes communicating to at least one mobile node within the time constraint T_{MAX}. is as follows.

$$P(1,N_m) = 1 - (1 - \frac{\Delta\theta R_{CC}^2}{2\pi})^{N_m T_{MAX}}. \tag{5.6}$$

According to the definition of OTR:

$$P(1,N_m) = 1 - (1 - \frac{\Delta\theta R_{CC}^2}{2\pi})^{N_m T_{MAX}} > C \tag{5.7}$$

$$\Longrightarrow R_{CC} > \sqrt{\frac{2\pi}{\Delta\theta}(1 - \sqrt[N_m T_{MAX}]{1-C})}. \tag{5.8}$$

Therefore, the optimal transmission range in this case is

$$OTR = \sqrt{\frac{2\pi}{\Delta\theta}(1 - \sqrt[N_m T_{MAX}]{1-C})}. \tag{5.9}$$

5.5.1.2 OTR for more than one cluster ($N > 1$)

Suppose there are $N > 1$ clusters of sensor nodes randomly deployed on the unit disk. Define A as the event that these N clusters can all be visited at least once by the mobile nodes within a specific period of time (T_{MAX}). The complementary set of A is the union set of $\overline{A}_i$,

$$P(\overline{A}) = P(\bigcup_{i=1}^{N} \overline{A}_i), \tag{5.10}$$

where A_i is the event that cluster i can be visited at least once within deadline (T_{MAX}). Therefore, the probability of the union set can be derived as [SFml]

$$P(\overline{A}) = P(\bigcup_{i=1}^{N} \overline{A}_i) = \sum_{n=1}^{N} (-1)^{n-1} C_n^N a_n, \tag{5.11}$$

where C_n^N is the n-permutation of N and a_n is the probability of the intersection of any n events $\overline{A}_i$,

$$a_n = P(\bigcap_{i \in I} \overline{A}_i), I \subset \{1, 2, \cdots, N\}, |I| = n, \tag{5.12}$$

$$a_n = (1 - n\frac{\Delta\theta R_C^2 C}{2\pi})^{N_m T_{MAX}}. \tag{5.13}$$

Therefore,

$$P(\overline{A}) = P(\bigcup_{i=1}^{N} \overline{A}_i) = \sum_{n=1}^{N} (-1)^{n-1} C_n^N a_n$$
$$= \sum_{n=1}^{N} (-1)^{n-1} C_n^N (1 - n\frac{\Delta\theta R_{CC}^2}{2\pi})^{N_m T_{MAX}}. \tag{5.14}$$

So, the probability that the N clusters can be visited at least once by one of the N_m mobile nodes within T_{MAX} is:

$$P(N, N_m) = P(A) = 1 - P(\overline{A})$$
$$= 1 - \sum_{n=1}^{N} (-1)^{n-1} C_N^n (1 - n\frac{\Delta\theta R_{CC}^2}{2\pi})^{N_m T_{MAX}}. \tag{5.15}$$

Therefore given N, N_m, T_{MAX} and C, we can always find the optimal R_{CC}.

5.5.2 OTR for Random Waypoint Model

The Random Waypoint Model (RWP) [RS03] is one of the most widely used mobility models in MWSNs. In this model, each mobile node moves in a convex domain along a zigzag path, where each of the straight line segments is called a *leg*. At each turning point, the node randomly chooses a new destination and then moves toward the destination at a constant speed independently drawn from a given speed distribution $f_V(v)$ at each turning point. We assume the mobile nodes choose each waypoint P_i from a uniform distribution over the unit disk, and on each *leg* between points P_{i-1} and P_i the mobile node velocity V_i is an *Identical Independent Distributed* (i.i.d.) random variable independent of the node location.

The probability density function (PDF) of the mobile node location following the RWP model on a unit disk is as follows [HLV06].

$$f(l) = \frac{45(1 - l^2)}{64\pi} \int_0^{\pi} \sqrt{1 - l^2 \cos^2 \phi}\, d\phi, \tag{5.16}$$

where l is the distance of the location to the original point. The PDF stated above can be approximated by a polynomial of the form:

$$P_L(l) = \frac{2}{\pi}(1 - l^2), \tag{5.17}$$

with the MSE of 6.5×10^{-4} [BW02]. Figure 5.4 shows the PDF of the location of the mobile nodes following the RWP model. As we can see, the mobile

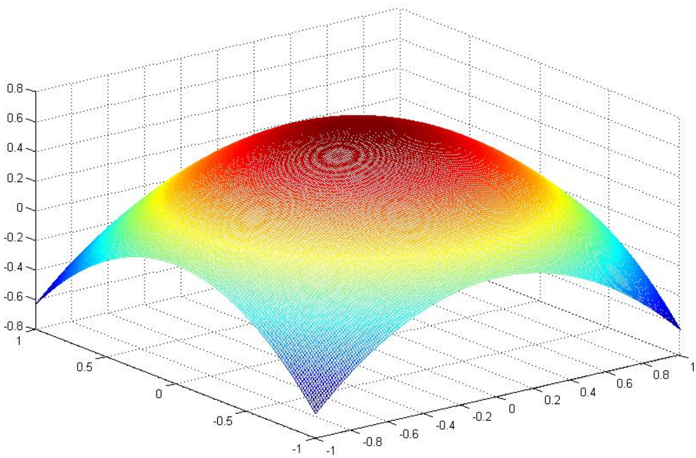


Figure 5.4: PDF of the location of mobile nodes in RWP model

nodes are more likely to be in the center of the disk rather than on the borders. Such a characteristic can be used to approximate the distributions of Taxis in the cities since as mentioned before, Taxis are also more likely to be in the city center than in the suburbs.

When talking about the arrival process of the mobile nodes of a coverage area, we can even make a local Poisson assumption and simply assume that for a single mobile node, the arrival process of this node within the area $B_r(l)$ results from a homogeneous Poisson point process with mean value equal to $f(l)|B_r(l)|$ [LHK05], in which $|B_r(l)|$ indicates the area of $B_r(l)$. Since the movement of each node is independent of others, the superposition of N_m mobile nodes also follows a Poisson distribution with mean equal to $N_m|B_r(l)|f(l)$.

5.5.2.1 OTR for one cluster ($N = 1$)

When there is only one cluster on the unit disk, the arrival rate of the mobile nodes within the transmission range of this cluster at each slot follows the Poisson Process with the mean, m, equal to

$$\frac{N_m \Delta\theta R_{CC}^2 f(l)}{2}. \tag{5.18}$$

Therefore, the probability of this sensor group not being visited at least once by the mobile nodes within this time slot is as follows [Refss].

$$P\{\Gamma(t+1)-\Gamma(t)=0\}=e^{-\frac{N_m \Delta\theta R_{CC}^2 f(l)}{2}} \tag{5.19}$$

where $\Gamma(t)$ indicates the arrival times of the mobile nodes within the transmission range from the initial time to time t.

Since the arrival rate follows the Poisson process, the arrival events of two different time slots are independent of each other. Therefore, the probability of the sensor group not being visited at least once within T_{MAX} is:

$$P\{\Gamma(t+T_{MAX})-\Gamma(t)=0\}=e^{-\frac{N_m T_{MAX} \Delta\theta R_{CC}^2 f(l)}{2}} \tag{5.20}$$

The event of the sensor group being visited once within T_{MAX} is the complementary of the above event (not being visited). Therefore, it follows to be:

$$P(N=1)=1-e^{-\frac{N_m T_{MAX} \Delta\theta R_{CC}^2 f(l)}{2}}. \tag{5.21}$$

The OTR in this case is then derived as the minimal transmission range that satisfies $P(1,N_m)>C$,

$$OTR=\sqrt{\frac{-2\ln(1-C)}{N_m T_{MAX}\Delta\theta f(l)}}. \tag{5.22}$$

5.5.2.2 OTR for more than one cluster ($N>1$)

When there are $N>1$ clusters located in the field, we can consider the arrival rate of the coverage areas of these N clusters to be independent of each other. Therefore, the probability that these N clusters can be visited at least once by the mobile nodes within the deadline (T_{MAX}) is

$$P(N,N_m)=\prod_{i=1}^{N} P_i=\prod_{i=1}^{N}(1-e^{-\frac{N_m T_{MAX} \Delta\theta R_{CC}^2 f(l_i)}{2}}), \tag{5.23}$$

in which P_i is the probability that cluster i ($i=1,2,\cdots,N$) will be visited by the mobile nodes at least once within T_{MAX} which is calculated as $P(N=1)$ in . The OTR can then be derived by calculating the minimum R_{CC} that satisfies $P(N,N_m)>C$.

In particular, if all the sensor groups are located on a circle with the center on the original point, all the sensor nodes share the same $f(l_i)$. In this case, $P(N,N_m)$ can be simplified as

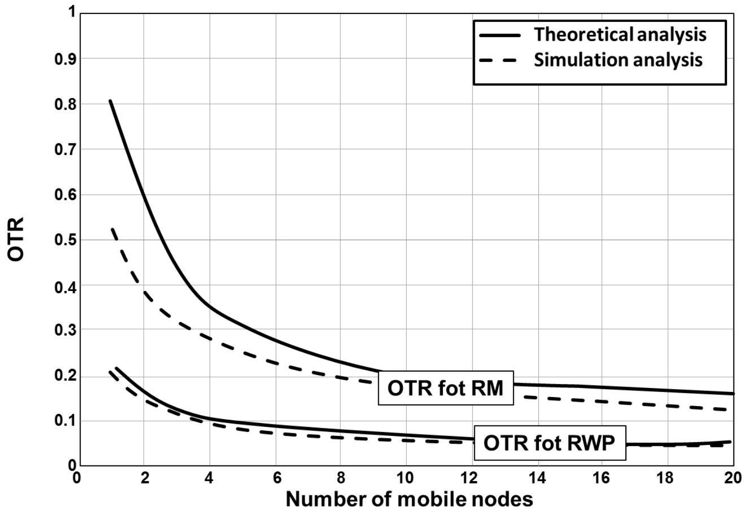


Figure 5.5: OTR expression verification of RW and RWP model

$$P(N > 1) = \prod_{i=1}^{N} P_i = (1 - e^{-\frac{N_m T_{MAX} \Delta\theta R_{CC}^2 f(l)}{2}})^N, \tag{5.24}$$

and

$$OTR = \sqrt{\frac{-2\ln(1 - \sqrt[N]{C})}{N_m T_{MAX} \Delta\theta f(l)}}. \tag{5.25}$$

5.5.3 Comparison of OTR for the Investigated Mobility Models

In the RW model, mobile nodes perform random walk on the unit disk resulting in a uniform location distribution at each time slot, whereas in the RWP model, mobile nodes choose their waypoints with a uniform distribution over the unit disk and the nodes then move to the waypoint with a random velocity with uniform distribution in $[V_{min}, V_{max}]$ and independent of the nodes' location.

Figure 5.5 shows the OTR results of the simulation experiments of RW and RWP models, and compares them to the theoretical results. Each simulation curve is the result of 10^8 simulation experiments of mobile nodes moving on a unit disc following the two models. The OTR is then calculated according to the definition as the transmission range that results in a probability of the clusters being visited by the mobile nodes larger than $C = 0.8$.

The Mean Square Error (MSE) of the theoretical results compared to the simulation results is:

$$E\{(OTR^{RW}_{theory} - OTR^{RW}_{simulation})^2\} = 0.0061 \qquad (5.26)$$

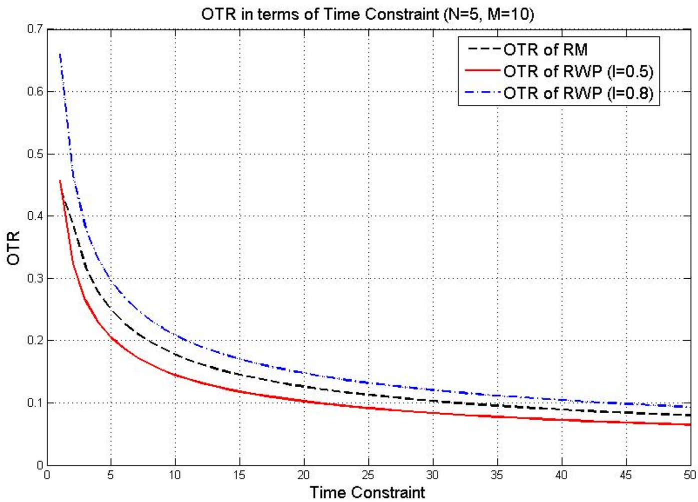
for RW model, and

$$E\{(OTR^{RWP}_{theory} - OTR^{RWP}_{simulation})^2\} = 4.5302 \times 10^{-4} \qquad (5.27)$$

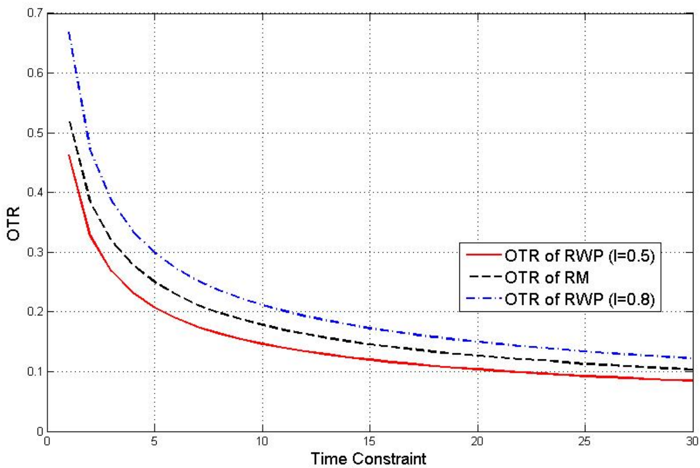
for RWP model, respectively that in comparison to the values of OTR are negligible. Such results verify that the theoretical expressions are comparatively accurate to estimate the OTR in both models. Similar verifications can also be done for multi-cluster cases.

Figure 5.6 shows the OTR in terms of time constraint for $N = 1$ and $N = 5$. From these results we can conclude that in both mobility models, the OTR decreases as the time constraint increases. The reason is that by increasing of the data collection time, mobile nodes will have a higher chance to visit the sensor nodes.

The OTR of RWP model is directly related to the location of the sensor nodes. From figure 5.6, we can see that the OTR of RWP model when the sensor clusters are located at $l = 0.5$ is smaller than the OTR of RW Model in both cases. However, the OTR of RWP model when the sensor clusters are located at $l = 0.8$ is larger than that of the RW Model. The reason is that based on the RWP model, mobile nodes are more likely to move near the center of the unit disk. Therefore, sensor nodes in this area need a smaller value of OTR to satisfy the desired data collection rate.



(a) OTR in terms of time constraint for $N = 5$ and $N_m = 10$



(b) OTR in terms of time constraint for $N = 1$ and $N_m = 10$

Figure 5.6: OTR in terms of time constraint (l is defined in equation 5.16)

5.6 Experiments on Beijing Taxi Trajectories

The heat-map plot of the data collections is presented in figure 5.1. Based on the improvement rate of the data collection by increasing the number of Taxis (figure 5.2) it is discussed that increasing the number of Taxis to improve the data collection rate is not an efficient solution. In this analysis, the CC-MWSN approach is applied to the experimental data of figure 5.1. For this sensor nodes are groupped in clusters of size 8 and utilize CC for scanning and data communication to mobile nodes. Statistics show that CC improves the data collection percentage from about 50% to 80%. In comparison to the standard MWSN case, relatively large blue areas indicating low data collection rate in specific parts of the city are fixed.

Figure 5.7 shows the OTR needed to gain a data collection of 80% for different number of Taxis. For instance, the OTR when using 4970 Taxis is only 300 m, whereas normally we only need 3 sensor nodes to collaborate to reach this transmission range. Such results show that using CC for data collection in mobile WSNs can efficiently improve the percentage of data collection.

The impact of CC-MWSN on energy consumption of the network in terms of Taxi numbers is shown in figure 5.8. The energy consumption of the sensor nodes is proportional to the transmission range. The energy consumption curves show that utilizing CC for data collection in such urban scale WSNs can efficiently decrease the energy consumption and at the same time guarantee the effective data collection comparing to the individual communication. However, increasing the number of nodes per cluster, N_m, does not necessarily decrease the energy consumption, since more C-nodes consume extra energy for local communication and data aggregation.

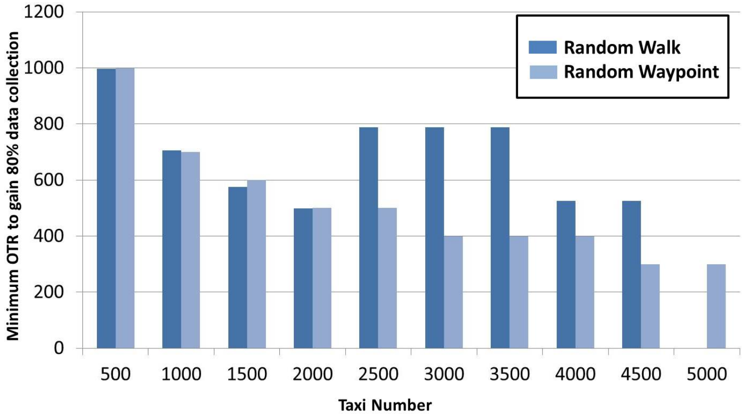


Figure 5.7: OTR in Beijing($C = 0.8$, 8am∼10am, May 1st, 2009)

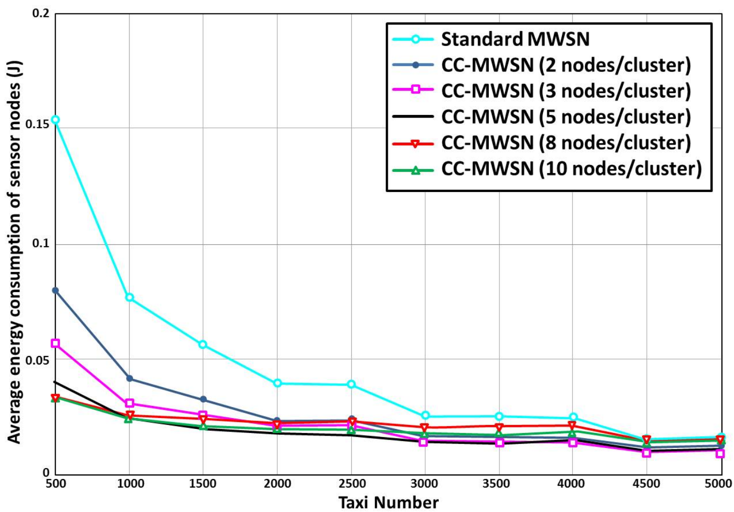


Figure 5.8: Average energy consumption of sensor nodes in terms of Taxi number

5.7 Summary

In this chapter, the application of CC in MWSN to improve the network connectivity was considered. In practice, the existing mobile objects in the sensing field are considered as mobile nodes. Despite of the cost efficiency of this idea, mobile nodes do not have appropriate mobility patterns. Therefore sensor nodes in certain areas are met by the mobile nodes very often, whereas those located in specific parts of the network suffer from very weak connectivity. For instance, in a sample urban sensing system, Taxis are used as mobile nodes. Therefore, the data of the sensor nodes at the city center is regularly collected, but sensor nodes at large parks or suburban areas might rarely meet the mobile node.

A specific version of CC was designed and implemented which is compatible to this scenario. After clustering, sensor nodes of each cluster utilize CC-R to detect the mobile nodes and send their data via CC-T. We further derived the optimal transmission range to achieve the minimized energy consumption in the Random Walk model as well as Random Waypoint model which can be utilized to estimate OTR in real-world deployments. Experiments on Beijing Taxi Trajectory dataset was conducted to verify the energy efficiency of utilizing CC in large scale WSNs with data collection ratio greater than 80%.

Chapter 6

Summary, Conclusion, and Potential Future Directions

In this thesis, the Collaborative Communication (CC) technique is extended and improved from various aspects, and subsequently applied to the two networking approaches in WSNs: Multi-Hop (MH) and Mobile Wireless Sensor Networking (MWSN), for improving the reliability and flexibility of data communication. Next section highlights the achievements and contributions of this thesis in terms of CC and collaborative networking (MH-CC and CC-MWSN) followed by proposing some directions for further extensions and future work.

6.1 Contributions

The focus of this thesis is primarily on two major areas:

- **CC:** a new version of CC, dubbed CC+, with higher reliability, energy efficiency, autonomy and flexibility is developed,
- **Collaborative networking:** CC+ is integrated into the two networking approaches in WSNs to provide a reliable and flexible data communication approach in extended networks in an autonomous way.

In the following section, the achievements of this research are discussed in detail.

6.1.1 CC+: A High Performance CC Approach

In chapter 2, the state of the art on CC techniques in WSNs, as well as their pros and cons, are reviewed. It is discussed that all of the existing approaches have inadequacies and drawbacks in terms of the distribution of the processing load, energy efficiency and/or flexibility. Therefore, the development of a high performance CC approach, dubbed CC+, is considered in chapter 3. For this, first the desired features of CC+ including high reliability and flexibility, energy efficiency, scalability and autonomous activity are defined. Then, one of the existing synchronization approaches with high potential to realize the above mentioned features, One-Bit Closed-Loop (OBCL), is selected as the starting point. Various ideas are proposed to achieve the desired features of CC+.

OBCL is an iterative synchronization approach with distributed processing load in which the synchronization accuracy gradually improves. This results in an acceptable flexibility as it allows the C-nodes to extend their transmission range flexibly by the modification of the synchronization accuracy. In addition, it uses one-bit feedback messages to increase its energy efficiency. However, it has a number of drawbacks, including:

- There is no consideration to select the minimum number of C-nodes, thus OBCL-based CC is not energy efficient.
- Potential C-nodes are unrealistically assumed to have the same rank when they join CC. It is experimentally shown that C-nodes with low quality signals have even negative effects on the overall performance of CC.
- OBCL-based CC only works in transmit-mode which results in a low network connectivity.

6.1.1.1 CC in Receive Mode (CC-R)

In the first step, the extension of the application of the OBCL-based CC technique to receive mode (CC-R) is considered. When CC-R is applied together with CC-T, a higher level of network connectivity is achieved. In the case of CC-T, there is no way for isolated nodes to contact the other nodes or in the case of connection, they are not able to improve their data communication performance due to the lack of C-nodes. However, in the case of CC-R, a group of C-nodes at the receiver side apply CC-R to collaboratively receive the signal of an isolated source node at a higher quality level, although the individual C-nodes receive the signal of the remote node with a low quality. It is shown that the major difference between CC-T and CC-R is in the arrangement of the C-nodes: In CC-T, C-nodes are at the proximity of the source whereas in CC-R, C-nodes are close to the destination. However, in both of them, the role of C-nodes is to provide multiple synchronized versions of the communicating signal at the destination. In addition, the phase shifts achieved in either CC-R or CC-T are valid for another one.

6.1.1.2 Development of Flexibility and Autonomy in CC

As the second step to reach CC+, the quality and number of C-nodes are considered. During experimental evaluations, it is observed that when the signals of C-nodes are at different quality levels, they would have different effects on the overall performance of CC. Therefore in chapter 3 novel ideas are proposed and implemented to select the high quality C-nodes. This approach improves the energy efficiency because it automatically selects the minimum number of highest-ranked C-nodes. However, the ranking metrics are not limited to those related to the signal quality. They can reflect the capability of sensor nodes in terms of their workload or energy storage level to regulate the energy consumption and activity of the nodes in the WSN.

In order to implement this idea, a multi-metric approach is considered for the ranking and selection of the C-nodes. Specific metrics which reflect the capability of the nodes to participate in collaboration are defined at sensor nodes in advance. Therefore sensor nodes are able to grade themselves in terms of their capability to act as C-node. The reference node (coordinator in CC-R or source in CC-T) broadcasts a request to its neighbors for joining to CC. A threshold level is also attached to this message representing the minimum acceptable grade of C-nodes. The entire neighbors calculate their overall grade and compare it with this threshold. Those having higher grades than the threshold participate in the collaboration as C-node. In this method, only highest-ranked C-nodes are selected. However, the minimum number of C-nodes is not yet achieved.

The threshold level directly controls the number of C-nodes. However, at the beginning, it is randomly selected, because the reference node has no idea about its distance with the remote node. In order to adjust the threshold level, the synchronization step is started. After synchronization, the destination compares the received power level from C-nodes to the desired level. The reference node uses the results to regulate the threshold. In CC-R the destination and the reference node are the same. However, in CC-T the source acts as the reference node. Therefore, the destination compares the signal level with its threshold and report the result to the source node. If the power level at the destination is higher than the desired level, the reference node selects a higher threshold to reject some of the C-nodes. Otherwise, a lower threshold is selected to add new C-nodes. This process is continued until the minimum number is achieved. Since after joining new C-nodes, the synchronization should be updated, it is preferred that a relatively low threshold or equivalently more C-nodes than what is really needed are selected in advance, because the rejection of C-nodes (by setting a higher threshold level) is simpler. In this way, CC+ selects the minimum number of highest-ranked nodes. Furthermore, reliability is also improved since the number of C-nodes is minimized subject to receiving an acceptable power level at the destination.

6.1.2 Integration of CC to Multi-Hop Routing

In chapter 4, a new platform, dubbed MH-CC, for multi-hop routing is proposed and implemented, which allowed almost all of the routing protocols to exploit CC for higher quality data communication and networking. The standard routing protocols are composed of two steps: route discovery and data transmission. The idea of MH-CC is to add a new *route correction* step after route discovery. So, after setting up of the multi-hop path between a particular pair of source and destination, the possibility of the application of CC to extend the length of hops along the multi-hop path is investigated. Those relay nodes which have enough number of C-nodes at their vicinity, run CC to jump over several of the next relay nodes and to directly connect to a farther one.

Analyses show that in terms of the number of nodes needed to connect a specific pair of source and destination, MH-CC is the same as the standard multi-hop. However, MH-CC increases the data communication reliability because of the transmission of the same data with a group of C-nodes. In the case of the failure of one or a few nodes, data is still delivered, although its quality slightly degrades due to the inadequate number of C-nodes. It is in the case that such failures in the standard multi-hop paths result in link breakage and the interruption of the data communication.

MH-CC is capable of flexible changing of the length of hops by the modification of the number of C-nodes or the synchronization accuracy at each relay. This approach would be applicable to compensate for the topological changes due to the dynamic situation or the variation of the sensor nodes activity e.g. the variation of the data generation rate. Due to the necessity of the autonomous modification of the transmission range extension, a procedure like what utilized in CC+ case is developed. The source or relay nodes which are responsible to hire C-nodes apply pre-defined metrics to figure out the appropriate setting of MH-CC.

6.1.3 Application of CC in Mobile WSNs (CC-MWSN)

Mobile Wireless Sensor Networking (MWSN) is another option which is widely used for networking in WSNs. MWSNs is composed of two types of nodes: sensor nodes which measure specific parameters and generate data, and mobile nodes which are responsible for data collection from sensor nodes by moving among them. In comparison with multi-hop, this networking approach has a better matching to the resource-restricted WSNs due to the simplicity of the sensor nodes' tasks. One major application of MWSNs is urban sensing. In an extended sensing field like a large city, a large number of sensor nodes (in the order of several hundred thousand or even millions) are deployed to cover the area. Multi-hop networking is not feasible in such scenarios because of the complex route discovery and maintenance process. Although sensor nodes are fixed, the movement of the obstacles (vehicles) and the variation of the transmission channel state result in a dynamic situation. In contrary, vehicles that continuously move all around the city can potentially act as mobile nodes in MWSN.

In a real-world project, a MWSN is utilized for measuring and monitoring the air pollution in Beijing city. In this network, 27,848 Taxis are applied for data collection of over 700,000 sensor nodes deployed in an area of 841 km^2. Since the paths of the Taxis cannot be optimized for data collection approach, there are some areas such as suburb or large parks in which sensor nodes are not regularly met and they might wait even a few days to deliver their data. As a numerical sample, the average percentage of the data collection during 2 hours by 5000 Taxis which are randomly selected is about 50%. Further analysis reveals that even increasing the number of Taxis would not have considerable effect on the increasing of the data collection percentage.

As a solution for the low coverage of mobile nodes in suburb area, we proposed the application of CC to increase the transmission range as well as the reception sensitivity of the sensor nodes. Sensor nodes are grouped into clusters and run CC-R to search for the mobile nodes. As soon as a mobile node is detected, sensor nodes run CC-T to deliver their data. Since sensor nodes are manually deployed, it is possible to install them in a particular arrangement, e.g. in the form of a circular array to gain higher performance, although other arrangements are applicable as well but with a lower performance. Analyses show that CC-MWSN improves the data collection efficiently. In the above-mentioned numerical example, the efficiency improves to more than 80%.

Different mobility models, including random-walk, random waypoint and the experimental models, are applied to determine the optimum transmission range of the sensor nodes. The direct result of this analyses is the estimation of the minimum transmission ranges to gain a certain data collection rate. However, the results are compared to find out the suitable mobility model for such scenarios. It is approved that waypoint model has the best matching to the Taxi trajectory traces in the experimental model. This achievement can be applied to design new networks.

6.2 Fulfilled Research Questions

In chapter 1, the low reliability and flexibility are considered as the major drawbacks of the data communication approaches in WSNs. It is also mentioned that appropriate solutions should properly suit the resource-restricted characteristic of sensor nodes. In other words, they should be energy efficient, autonomous with a slight computational load and distributed structure. In this section, it is discussed how these goals are realized during this dissertation.

6.2.1 Reliable Data Communication

The major idea to increase the reliability of data communication is the application of CC approach. Since a group of nodes transmit or receive the same signal, even if one or a few of them are failed or leave the network, the link is still working, although it results in a slight decrease of the quality of the received signal. In comparison with the standard multi-hop, MH-CC applies the same number of nodes to connect a particular pair of source and destination. However, due to the above-mentioned feature of CC, MH-CC based links would have higher reliability.

6.2.2 Flexible Data Communication

As mentioned in chapter 3 and 4, the reliability and energy cost of CC vary as the functions of the number of C-nodes and synchronization accuracy. It is showed that there are certain settings for the effective factors which result in energy efficient, reliable or a moderate case of data communication. Each setting can be autonomously acquired by C-nodes. In addition, MH-CC is flexible in terms of the length of relays. This flexibility can be applied to e.g. jump over the inappropriate relay nodes. On the other hand, CC-MWSN efficiently allows sensor nodes to modify their transmission range by the selection of specific group of sensor nodes.

6.2.3 Autonomous Data Communication

Both MH-CC and CC-MWSN are capable of adapting to the topological changes of the network or the variation of some parameters which affect the data transmission quality such as the data generation rate. For this, appropriate metrics are defined in advance, based on which sensor nodes are able to find the optimum setting to compensate for the impact of the dynamic situation on data communication.

6.3 Potential Directions for Further Extension

MH-CC and CC-MWSN, as the two high quality data communication approaches, have deep effect on WSNs applications. The current research is however the first study in this area, therefore it does not cover the entire issues regarding collaborative data communication and networking in large scale scenarios. In this section, some directions to extend this novel approach are proposed.

6.3.1 Development of MAC Layer Techniques Compatible with CC

In the current work, techniques from Physical and Network layers are integrated. In both MH-CC and CC-MWSN approaches, sensor nodes need to apply MAC layer techniques to access the channel. Since the focus of this work is on the Physical and Network layers, a standard channel access technique is considered. Although the current design properly works, the modification of channel access approaches to match the CC technique would increase the data communication performance because of the higher match of various elements of the communication stack. In [BDS$^+$12], we have presented a context sensitive channel access approach which senses and controls the collision rate by adaptively modifying the exponential back-off approach which is originally applied to control the collision rate. It can be applied as a starting point for the extension of a channel access approach which appropriately matches to MH-CC.

6.3.2 Integration of CC into Location-Aware WSNs

MH-CC approach developed in chapter 4 is based on the assumption of relative location information in sensor nodes. In other words, sensor nodes are only aware of the list of their neighbors, but their absolute positions or the position of the destination is not known. In the case of location-awareness, sensor nodes are aware of their absolute position which would have deep effects on both routing and CC approaches. In terms of routing, the source nodes exactly know which of the neighbors would be an appropriate relay node to send their data to the destination. The impact of the location information on the CC approach is even more. C-nodes are able to steer their beam-pattern through a specific direction without needing a remote node for synchronization. Therefore, MH-CC in location-aware networks would be totally different than the current version:

- The implementation of MH-CC in the case of location information would be simpler due to its less interaction for synchronization. The implementation of MH-CC in the case of location information would be simpler due to its lesser interaction for synchronization
- The extension of the transmission range in CC-R to connect to isolated

nodes is possible.

- For the development of a path between a specific pair of source and destination, the discovering of a multi-hop path is not necessary.
- A more efficient C-node selection approach based on their location information is feasible.

Therefore, one potential direction to extend the current work would be to apply MH-CC routing to location-aware WSNs.

6.3.3 Development of Autonomy and Flexibility in CC-MWSN

The CC-MWSN approach developed in chapter 5, perfectly matches to the resource-restricted sensor nodes as they do not need to carry out complex processing such as route discovery or maintenance. They simply search for mobile nodes and transmit their data when one mobile node is detected at their vicinity. Furthermore, because of the low capabilities of the sensor nodes, only a fixed collection rate is considered for the network. Therefore a minimum transmission range extension is estimated to satisfy the desired collection rate. Then, the network design criteria, including the number of nodes per cluster and the arrangement of the nodes in a cluster, are fulfilled based on the estimated transmission range. WSNs have, however, dynamic situation in terms of the position of the nodes or data communication objectives which should be compensated during data communication. It emphasizes the need for the development of autonomy and flexibility in CC-MWSN. Therefore it is proposed as a potential direction for the extension of the current work.

One potential way to develop flexibility would be to define different sub-arrays at each cluster and controlling the data collection rate by regulating the transmission range extension. The difference between sub-arrays is in the number of their C-nodes which directly affects the transmission range extension as well as energy consumption. Therefore various sub-arrays can be applied to gain different levels of network connectivity and data collection rate.

In addition, similar to the autonomous ideas applied in chapter 4, it is possible to autonomously select appropriate sub-array. For this, a specific parameter e.g. the data generation rate is defined to be followed by CC-MWSN.

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List of Figures

1.1 Single-hop collaborative communication 3
1.2 Comparison of the quality of data communication in cases of MH and MH-CC 5
1.3 Illustration of the positive effects of CC on the network connectivity of MWSNs 6
1.4 Research methodology and structure of the thesis at a glance 8
1.5 Research methodology and structure of the thesis in detail . . 11

2.1 A view of a typical sensor node 14
2.2 Direct data communication between sensor nodes and destination 18
2.3 Hierarchical data communication in cluster-based WSNs . . . 19
2.4 Data communication in multi-hop WSNs 19
2.5 A view of the standard beamforming systems 21
2.6 Illustration of the arrangement of C-nodes and destination in CC 22
2.7 Impact of frequency error on the performance of CC-T 24
2.8 Impact of phase error on the performance of CC-T 26
2.9 Round-trip synchronization approach 28
2.10 Search space of (1+1)-EA synchronization approach [SB08b] . 31
2.11 Master-slave phase synchronization 33
2.12 Data communication in mobile WSNs 40

3.1 A sample scenario to show the impact of CC-R on the network connectivity 48
3.2 A general view of CC-R 49
3.3 The standard structure of receive beamforming 50
3.4 Comparison of CC-T and CC-R in a systematic view 55
3.5 Relation of the signal quality to the received SNR and modulation order [PS07] 57
3.6 WSN model considered to extract the minimum number of C-nodes 58
3.7 Comparison of the signal quality in terms of BER with and without the application of CCE 64
3.8 Impact of the number of C-nodes on BER (Labels of the curves represent the average SNR at C-nodes) 65

3.9 Experimental performance evaluation of receive collaboration 66
3.10 Comparison of the BER level of C-nodes and CC-R output of set I and II 68
3.11 Impact of the selection of the best M nodes on the collaboration energy efficiency: 40 nodes participate in the collaboration and only M of them are selected 72
3.12 Comparison of the minimum number of C-nodes to gain different levels of BER for the proposed and conventional methods 73
3.13 Illustration of the positive impact of the proposed algorithm on the lifetime 75

4.1 Comparison of data communication in MH and MH-CC in extended WSNs 79
4.2 Comparison of the number of potential relay nodes in MH and MH-CC (for $M = 3$ C-nodes) 81
4.3 Different elements of a MH-CC path 81
4.4 Route correction in MH-CC routing 83
4.5 Route maintenance in MH-CC routing when a CR-node is failed 88
4.6 The proposed solution of C-node failure problem 90
4.7 The behavior of phase and output power at OBCL synchronization technique 94
4.8 Illustration of the OBCL synchronization efficiency for different values of M 95
4.9 Scenario considered to analyze reliability and energy efficiency 99
4.10 The impact of MH-CC on the reliability for different lengths of messages and mobility modes 100

5.1 Data collection pattern in Beijing performed by 5000 within 2 hours 107
5.2 Data collection percentage in Beijing city for different numbers of Taxis 107
5.3 Sensor nodes at each cluster use CC-R to detect a mobile node and then use CC-T for data communication 109
5.4 PDF of the location of mobile nodes in RWP model 117
5.5 OTR expression verification of RW and RWP model 119
5.6 OTR in terms of time constraint (l is defined in equation 5.16) 121
5.7 OTR in Beijing($C = 0.8$, 8am$\sim$10am, May 1st, 2009) 123
5.8 Average energy consumption of sensor nodes in terms of Taxi number 123