Resilient Wireless Sensor Networks

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Statement of Authorship/Originality

I certify that the work in this thesis has not been previously submitted for a degree nor has it been submitted as a part of the requirements for other degree except as fully acknowledged within the text.

I also certify that this thesis has been written by me. Any help that I have received in my research and in the preparation of the thesis itself has been fully acknowledged. In addition, I certify that all information sources and literature used are quoted in the thesis.

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Abstract

With the increase in wireless sensor networks' (WSN) applications as the result of enhancements in sensors' size, battery-life and mobility, sensor nodes have become one of the most ubiquitous and relied-upon electrical appliances in recent years. In harsh and hostile environments, in the absence of centralised supervision, the effects of faults, damages and unbalanced node deployments should be taken into account as they may disturb the operation and quality of service of networks. Coverage holes (CHs) due to the correlated failures and unbalanced deployment of nodes should be considered seriously in a timely manner; otherwise, cascaded failures on the rest of the proximate sensor nodes can jeopardise networks' integrity. Although different distributed topology control (TC) schemes have been devised to address the challenges of node failures and their dynamic behaviours, little work has been directed towards recovering CHs and/or alleviating their undesirable effects especially in Large Scale CHs (LSCH). Thus, devising CH recovery strategies for the swift detection, notification, repair and avoidance of damage events are important to increase the lifetime and resiliency of WSNs and to improve the efficacy and reliability of error-prone and energy-restricted nodes for many applications. In this research, the concepts of resiliency, fault management, network holes, CHs, TC schemes and stages of CH recovery are reviewed. By devising new TC techniques, CHs recovery strategies that partially or wholly repair LSCHs and increase the coverage of WSNs are presented such that a global pattern emerges as a result of nodes' local interactions.

In this study, we propose **(1)** CH detection and boundary node (B-node) selection algorithms, which B-nodes around the damaged area self-select solely based on available 1-hop information extracted from their simple geometrical and statistical features. **(2)** A constraint node movement algorithm based on the idea of virtual chord (v-chords) formed by B-nodes and their neighbours to partially repair CHs. By changing each B-node's v-chord, its movement and connectivity to the rest of network can be controlled in a distributed manner. **(3)** Fuzzy node relocation models based on force-based movement algorithms are suitable to consider the uncertainty governed by nodes' distributed and local interactions and the indefinite choices of movements. **(4)** A model of cooperative CHs recovery in which nodes move towards damaged areas in the form of disjoint spanned trees, which is inspired by nature. Based on nodes' local interactions with their neighbours and their distances to CHs, a set of disjoint trees around the CH spans. **(5)** A hybrid CH recovery strategy that combines sensing power control and physical node relocation using a game theoretic approach for mobile WSNs. **(6)** A sink-based CH recovery via node relocation where moving nodes consider the status of sink nodes.

The proposed node relocation algorithm aims to reduce the distances of moving nodes to the deployed sink nodes while repairing the CHs. The results show that proposed distributed algorithms **(1)-(6)** either outperform or match their counterparts within acceptable ranges.
The significances of proposed algorithms are as follow: Although they are mainly designed base on the available 1-hop knowledge and local interactions of (autonomous) nodes, they result in global behaviours. They can be implemented in harsh and hostile environments in the absence of centralised operators. They are suitable for time-sensitive applications and scenarios with the security concerns that limit the amount of information exchange between nodes. The burden of decision making is spread among nodes.

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List of Abbreviations

ADL	Absolute Degree Loss
AVD	Average Distance from Damaged Area
aM-CSSCMM	M-CSSCMM based on the amplitude
B-B cell	B-Node Voronoi Cell Neighbour with B-node Voronoi Cell
B-D cell	B-Node Voronoi Cell Neighbour with D-node Voronoi Cell
B-node	Boundary Node
BNS-Algorithm	Boundary Node Selection Algorithms
CA	Cellular Automata
CCP	coverage configuration protocol
CH	Coverage Hole
CHR	Coverage Hole Recovery
CHD	Coverage Hole Detour
CI	Confidence Interval
CLAvgB	Cosine Law Average Boundary
CLMinB	Cosine Law Min Boundary
CM	Center of Mass
C-Mobility	Controlled Mobility
CNF-algorithm	Closer Nodes First Algorithm
CP	Candidate Parent

CSSCMM	Combined SS and CM Movement
D-area	Damaged Area
D-event	Damage Event
D-node	Damaged Node
DHSCL	Distributed Homogeneous Synchronous Coverage Learning Algorithm
dM-CSSCMM	M-CSSCMM based on the angle
DN-node(s)	Damaged Neighbour Node(s)
DSN	Distributed Sensor Network
DSSA	Distributed Self-Spreading Algorithm
DS-Tree	Disjoint Spanned Tree
DUCM-Algs.	DN-nodes and UN-Nodes' Centre of Mass Algorithm
EC	Emergent Cooperation
ECE	Efficiency of Consumed Energy
FAM	Fuzzy Angular Movement
FARM	FAM then FRM
FRM	Fuzzy Radial Movement
FRAM	FRM then FAM
FRNAM	FRM and FAM
GPS	Global Positioning System
HBD	Hole Boundary Detection
LSCH	Large Scale Coverage Hole
k-RSC	k-redundant sensing coverage
MANETS	Mobile ad hoc networks
MAS	Multi-Agent System
MaxD-algorithm	Maximum Distance Algorithm
MinD-algorithm	Minimum Distance Algorithm

MB-node(s)	Margin of Boundary node(s)
M-CSSCMM	Modified CSSCMM
MWSNs	Mobile WSNs
N-node	Normal Node
NE	Nash equilibrium
Perc-k-RSC	percentages of k-redundant sensing coverage
PCov	Percentage of Coverage
PP	Potential Parent
PSO	Particle Swarm Optimization
QoS	Quality of Service
RBN	Random Boundary node
RDL	Relative Degree Loss
R_c	Transmission Range
R_s	Sensing Range
RE	Residual Energy
ROI	Region Of Interest
QB	Quantile-based (comparative) Boundary
S-Coverage	Spatial Coverage
SB-Node	Selected Boundary Node
SS	Simple Sink
SSCH	Small Scale Coverage Hole
SSM	Simple Sink Movement
T-Coverage	Temporal Coverage
TC	Topology Control
TS	Takagi and Sugeno
UAV	Unmanned aerial vehicle
U-node	Undamaged Node

UDG	Unit Disk Graph
U-Mobility	Uncontrolled Mobility
UN-node	Undamaged Neighbour Node
V-chord	Virtual Chord
V-Hole	Virtual Hole
V-node	Virtual Node
VA-Algorithm	Voronoi Area Algorithm
VarD-Algorithm	Variance of Distance Algorithm
VD-Algorithm	Voronoi Distance Algorithm
WQB	Weighted quantile-based Boundary
WSN	Wireless Sensor Network