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Reliable and Energy Efficient Cluster-Based Wireless Sensor Networks

by

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Thesis submitted to the Faculty of Graduate and Postdoctoral Studies

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Abstract

This thesis revolves around the Cluster-Head (CH) operations to provide an energy efficient and data reliable cluster-based Wireless Sensor Network (WSN). The tasks of the CH are very energy intensive and its role is vital in order to keep the network alive and provide maximum network coverage. It requires energy efficient protocols to extend the lifetime of the network and provide reliability to the clusters.

To have an energy efficient cluster-based sensor network we propose a new paradigm for MAC layer protocols and provide a Dynamic Slot Assignment (DSA) scheme for TDMA-based MAC protocols in low activity sensor networks. In this scheme, based on the network activity, the connection is established between the cluster-head node and those sensor nodes which have data to send, and a TDMA slot is assigned to each of them dynamically. Then we present Dynamic TDMA Slot Scheduling (DTSS) scheme on top of the DSA scheme to improve the channel utilization and connection blocking probability with the introduction of some packet dropping probability. DTSS achieves this by enabling multi-slot assignment to the sensor nodes and slot-stealing from the less active sensor nodes. A Markov chain based mathematical model has been presented for both DSA and DTSS schemes for correlated connection arrival and we prove the viability and performance of the presented schemes numerically.

Usually in the cluster-based WSNs, the CHs are rotated after a round to distribute the CH responsibility. The cluster stability collapses when the CH dies due to any reason. To provide cluster stability, this thesis proposes to have a Backup Cluster-Head (BCH) for those CHs which may not be able to continue for the whole round due to energy constraint. The BCH takes over the CH responsibility before it depletes and becomes the new CH, hence keeps the cluster stable. The performance has been evaluated based on the simulations. A Markov chain model is also presented to analyze the cluster reliability. We use non-homogeneous Markov process, along with Forward Chapman-Kolmogorov equations to illustrate the cluster monitoring period in a finite three state space model. We test the accuracy of the model. The results show that the presented model matches the behaviour of the cluster state transition and validates the simulation results and analysis.

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*To the loving memory of my late father Amanullah Hashmi,
to my mother Amina Khatoon
and
to all those who are involved
in the effort to save the humanity
from the eternal failure
of the hereafter*

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Glossary

2CRNDC	2-Connected Relay Node Double Cover
AFN	Aggregation and Forwarding Nodes
AI-MAC	Adaptive Information-centric Lightweight MAC
AN	Access Nodes
APTEEN	Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol
BCH	Backup Cluster-Head node
BMA	Bit-Map-Assisted
BS	Base Station
CAR	Congestion-Aware Routing
CDMA	Code Division Multiple-Access
CH	Cluster-Head node
CM	Clustering with Mobility
CP	Contention Phase
DBCH	Double Backup Cluster-Head
DGRAM	Delay Guaranteed Routing and MAC
DSA	Dynamic Slot Assignment
DSC	Dynamic/Static Clustering protocol
DS-SS	Direct-Sequence Spread Spectrum
DTMC	Discrete-Time Markov Chain
DTSS	Dynamic TDMA Slot Scheduling

EA-TDMA	Energy-efficient Adaptive TDMA
EDETA	Energy-efficient aDaptive hiErarchical and robusT Architecture
EEG	ElectroEncephaloGram
EERNT	Energy-Efficient Redundant Nodes Tree
EMACs	Energy efficient MAC for sensors
FDMA	Frequency Division Multiple-Access
FEED	Fault tolerant, Energy Efficient, Distributed clustering
FLAMA	FLow-Aware Medium Access
FlexiMAC	Flexible MAC
FlexiTP	Flexible TDMA Protocol
FLOC	Fast LOcal Clustering service
FT-DSC	Fault Tolerant Dynamic Static Clustering
G-MAC	Gateway MAC
GTIM	Gateway Traffic Indication Message
HART	Highway Addressable Remote Transducer
HEED	Hybrid Energy-Efficient Distributed clustering
LASA	Low-energy Adaptive Slot Allocation
LEACH	Low-Energy Adaptive Clustering Hierarchy
LMAC	Lightweight Medium Access Control
MAC	Media Access Control
MCAR	MAC-enhanced Congestion-Aware Routing
MCMAC	Mobile Cluster MAC
MEMS	Micro Electro-Mechanical Systems
MMDP	Markov Modulated Deterministic Process

MMPP	Markov Modulated Poisson Process
MTTF	Mean Time To Failure
PACT	Power Aware Clustered TDMA
PBEACP	Priority-based Energy Aware and Coverage Preserving
PEDAMACS	Power Efficient and Delay Aware Medium Access Control protocol
PMAC	Position-enabled MAC
RMAC	Randomized MAC
RST	Rapid Spanning Tree
RSTP	Rapid Spanning Tree Protocol
SAFE	Sinks Accessing data From Environments
SAS/IML	Statistical Analysis System/interactive matrix language
SEES	Smart Energy Exploitation and Sharing
SFRP	Selective Flooding-based Routing Protocol
SMACS	Self-organizing Medium Access Control for Sensor networks
SMP	Semi-Markov Process
SS-TDMA	Self-Stabilizing TDMA
TDMA	Time-Division Multiple-Access
TDMA-ASAP	TDMA-Adaptive Slot-stealing And Parallelism
TEEN	Threshold sensitive Energy Efficient sensor Network protocol
TRAMA	TRaffic Adaptive Medium Access protocol
TSMP	Time Synchronized Mesh Protocol
WBDiff	WinBUGS Differential Interface
WinBUGS	Bayesian inference Using Gibbs Sampling for Windows
WSN	Wireless Sensor Network

List of Symbols

$1/\mu$	Mean of the connection duration of each sensor node
a	Sensor activity factor in percentage
A	Average number of slots occupied by all the sensor nodes
b	Data size in bytes
B	Rate of channel blocking at the data channel
C	Number of clusters
ChU_{DSA}	Channel utilization for DSA model
d	Distance
D	Average number of dropped packets per frame
d_{CH}	Distance from the node to the CH
$d_{crossover}$	Cross-over distance
DLR	<i>Data Loss Ratio</i> is a ratio of the difference of total data sent by the sensor nodes and received at the base station to the total data sent by the sensor nodes
DP	Packet dropping probability in the DTSS model
E_1	Traffic channel efficiency for DSA model
E_2	Traffic channel efficiency for DTSS model
E_{agg}	Energy spent on computing and aggregating the data
E_{CH}	Energy consumption by a CH during a single frame
$E_{CH \rightarrow BS}$	Energy consumed to transmit the data to the base station
E_{CHc}	Energy consumed by CH in transmitting this control signal
$E_{CHcost/rnd}$	Average energy consumption of a CH in a single round

$E_{CHcost/sec}$	The average energy consumed by a CH per second
E_{CHres}	Residual energy of the CH
$E_{clus/round}$	Energy dissipated by all the nodes in a single cluster per round
E_{idle}	Energy dissipated by a node in idle listening the channel
E_{ini}	Initial energy of every sensor node at the start of a network
$E_{MAXinCluster}$	Highest energy of the sensor in the whole cluster
E_{proc}	Sensor's processing energy due to radio electronics cost
E_{res}	Residual energy of the sensor node
E_{Rx}	The amount of energy used when receiving a message
E_{SN}	Energy used by each non-CH sensor node
$E_{SN\leftrightarrow CH}$	Energy dissipation by a sensor node or a CH, transmitting data to each other
E_{tdma}	Total energy consumed by the network in a round by TDMA-based protocols with α activity
E_{total}	Total energy dissipated during a round by all N sensor nodes in the network
E_{Tx}	The amount of energy used for sending a message
E_e	Threshold energy level, below which a CH is susceptible to fail
f	Number of frames
G_r	Gain of the receiving antenna
G_t	Gain of the transmitting antenna
h_r	Height of the receiving antenna above the ground
h_t	Height of the transmitting antenna above the ground
L	System loss factor

M	Maximum number of connected nodes in a cluster
m	Total number of active nodes in the cluster
m_{ave}	Average number of sensor nodes connected out of M possible connections in every frame
N	Number of sensor nodes in the network
n	Total number of time slots in a TDMA frame
$P(k)$	Probability that all M sensor nodes occupy k slots
$P(k m)$	Probability that m sensor nodes occupy k slots
$P(M)$	Connection blocking probability
$P(m),$	Probability of m sensor nodes connected in a cluster
$P'(k)$	Probability that all M sensor nodes occupy k slots with less radio resources
$P_{BCH \rightarrow 0}(t)$	Probability of BCH energy depleting to zero level
$P_{CH \rightarrow L}(t)$	Probability of CH energy going towards the threshold energy level
P_{error}	Probability of wireless channel error
P_r	Receive power
$\mathbf{Pr}(t)$	state probability vector at time t
P_t	Transmit power
q	Max number of slots that can be assigned to a sensor node
R	Rate of rejection of the packets at the signalling channel
r	Size of a connection-request packet (in bytes)
rnd	The duration of a round
S	Mean of the output of each signalling channel slot
s	Size of control message from CH (in bytes)

$S_B(t)$	Steady state probability of being in <i>Backup</i> state
$S_F(t)$	Steady state probability of being in <i>Fail</i> state
$S_N(t)$	Steady state probability of being in <i>Normal</i> state
t	Time
$t_{BUthresh}$	BCH wakeup time or Backup threshold time
T_c	The contention period
T_s	The period of a time slot
U	Length or width of the network region
v	The number of slots in signalling channel
w	Number of sensor nodes per cluster
x	Correlation-factor
X	Normalization factor for $P'(k)$
α	Network activity factor
γ	Wavelength of the carrier signal
$\Delta(t)$	Markov chain transition probability matrix at time t
ϵ_{fs}	Free space path loss for distances less than $d_{crossover}$
ϵ_{mp}	Multipath loss for distances more than $d_{crossover}$
$\theta_{BB}(t)$	Probability that the cluster remains in the <i>Backup</i> state
$\theta_{BF}(t)$	Transition probability from the <i>Backup</i> state to the <i>Fail</i> state
$\theta_{FF}(t)$	Probability that the cluster remains in the <i>Fail</i> state
$\theta_{ij}(t)$	Transition probabilities of going from state i to state j in a Non-homogeneous Markov chain
$\theta_{NB}(t)$	Transition probability from the <i>Normal</i> state to the <i>Backup</i> state
$\theta_{NF}(t)$	Transition probability from the <i>Normal</i> state to the <i>Fail</i> state

$\theta_{NN}(t)$	Probability that the cluster remains in the <i>Normal</i> state
λ	Mean of the arrival of connection requests
ρ	Traffic intensity for the sensor data traffic
$\sigma(x, y)$	Node distribution in the region

Chapter 1

Introduction

1.1 *Background*

Wireless Sensor Networks (WSNs) have emerged as a viable tool for monitoring the physical world, by exploiting the self-organizing network capability of battery-powered wireless sensors. It can be used for many applications, such as battlefield surveillance, biological detection, home security, habitat monitoring, in-door monitoring, target tracking etc [AKY-02]. A WSN consists of small sensing devices, deployed in a region of interest. Each device has sensing, processing and wireless communication capabilities, which allow it to obtain information about the environment and to report to the Base Station (BS) or a remote user. The BS aggregates and analyzes the data received from the sensor nodes and then acts accordingly. Transmission of the data to the BS can be done by relaying it through the neighbouring nodes, hop by hop in the direction of the BS. Another way is to choose a leader as a relay agent for every cluster of selected nodes as a first hop, and then the leaders relay the data either directly or via each other to the BS. The latter method is employed in the cluster-based WSNs.

The routing protocols for cluster-based WSN, are scalable and energy efficient. A lot of work is done on the efficient cluster formation in order to achieve long lasting and energy efficient network. Low-Energy Adaptive Clustering Hierarchy (LEACH) is one of the early protocols that proposed the hierarchical sensor network, based on clusters [HEI-00]. In cluster-based sensor networks, a Cluster-Head node (CH) is assigned to each cluster from the sensor nodes. In order to prolong the network lifetime and to avoid the single

point of failure, the CH responsibility is rotated among the sensor nodes, which distributes the workload on all the sensor nodes. This rotation occurs after every stipulated period, called as round. In the beginning of the round, there is a setup phase, where the CH and sensor nodes are selected for each cluster. Then the steady-state period starts where the sensor nodes collect the data and transmit them to their respective CH.

Usually in a cluster-based WSN, the role of the CH is imperative. The main task of a CH is to receive the data from the sensor nodes that are in its cluster, aggregate the received data and then transmit the aggregated data to the BS. It acts as a gateway for the sensor nodes of its cluster. The CH may also act as a router for other CHs and relay the data towards the BS. In fact, the CHs, which are the gateway of their clusters, may be used as the backbone of the network. Additionally, a CH may also perform other control functions for cluster members such as serving as an arbiter for channel access of its own cluster. Hence, due to so many tasks, the energy consumption of a sensor node dramatically increases when it becomes a CH.

In cluster based sensor networks, the CH has also a pivotal role. If a CH of any cluster collapses or dies due to energy depletion or due to hostile working environment where they can have physical damage, then the sensor nodes of the entire cluster lose the scope. This work revolves around the CH operations, in order to provide an energy efficient and data reliable WSN.

1.2 *Motivation and Objectives*

WSNs are becoming a viable tool for many monitoring applications. These applications may be of critical nature where the transportation of the information of events from the region of interest to some BS or sink is crucial and the data loss can not be tolerated. In the other direction, the information (for the purpose of control or management) sent from the base station to the sensor nodes can be very sensitive to loss as well. For example, in re-tasking sensor nodes, sending a program image to them is challenging. The loss of a single message, associated with the program code, will leave the image useless and the whole re-tasking process will fail.

Mostly in existing cluster-based WSNs, the CH of the clusters are rotated among all the

sensor nodes after each round, which increases the network lifetime and distributes the CH responsibility on every sensor node. The energy of the sensor nodes is heavily consumed when they become the CH. Rotation of the CH responsibility causes the energy of all the sensor nodes to go down almost together, to such an extent that after a point if any sensor becomes a CH, its energy may exhaust while being a CH and may not be able to continue to the end of the round. In the next round, a new CH may be chosen but until then, that cluster area is totally unmonitored and the guaranteed coverage of that region is lost. The information gathered by that CH is also lost at that point. If the steady-state phase is shortened to reduce the loss, it will increase the overhead of setup phase and still there will be losses due to the death of the CHs.

These data losses can be vital. The data transfer reliability in the WSN is of huge importance for critical applications where the loss of single information about any event is crucial. Suggested Transport Layer Protocols do provide end-to-end reliability or reliable transfer of the data from a source to a destination, but they do not cater to the data loss due to the failure of the CHs.

The CH failure scenario arises when no sensor node in the network is capable to run the whole round alone. So a sensor even with the highest residual energy will be susceptible to fail before the completion of the round. Our first objective is to reduce this data loss due to the CH failure during a round and provide a continued coverage to that cluster until the new round starts with a new CH.

The cluster-based WSN usually use Time-Division Multiple-Access (TDMA) based Media Access Control (MAC) protocols for channel access and Direct-Sequence Spread Spectrum (DS-SS) based Code Division Multiple-Access (CDMA) codes for channel usage to avoid inter-cluster interference [CIO-08]. TDMA allows every node to eventually transmit its own data. It assigns sensor nodes their own time slot and they access the shared medium only in this time slot. They transmit data in a round robin fashion and thus avoid collisions. Most of the suggested works that used TDMA-based MAC scheme assumed that the sensor nodes have periodic data and occurrence of the events is always deterministic. Hence, they assumed that there will always be enough data to fill their transmission slots entirely and the transmission channel will always be busy using the

channel bandwidth efficiently. But in reality, this is not always true. There are many applications where events take place non-deterministically with inconsistent activities in the network, which result in varying data traffic where many sensor nodes may or may not have data to send. Assigning a time slot in the frame to a node, which has no data to send, wastes the channel bandwidth and sensor's energy.

The second objective of this thesis is to provide an energy efficient MAC scheme for low activity sensor networks. This MAC scheme also caters to the bursty traffic nature and at the same time is robust and scalable.

1.3 ***Thesis Contributions***

The objectives given above have been addressed throughout this thesis. Our primary contributions and accomplishments include the following.

- We have introduced a new idea that provides the maximum coverage of the network in terms of times and reduces the data loss sensed and sent by the sensor nodes. We have hereby introduced the idea that in any existing clustering protocol, select Backup Cluster-Head nodes (BCHs) for those CHs whose residual energy level is already at a certain threshold. The original CH, when gets closer to the point of depletion of energy, sends an SOS signal to the BCH, which takes over the responsibility by becoming the CH, hence provides the continuous monitoring of the network. We have evaluated the BCH algorithm with computer simulation and have proved its efficiency.
- We have modeled the cluster reliability of BCH-based clustered WSN, using a Markov chain model. We have used a non-homogeneous Markov process and have adopted the Forward Chapman-Kolmogorov equations to compute the cluster states in a finite three state space model. We have tested the model and have showed that the proposed model is able to accurately match the behaviour of the cluster state transition. We can apply the proposed Markov chain based model to any three-state fault-tolerance system with varying transition probabilities and a given initial state probability vector.
- We have also presented the Dynamic Slot Assignment (DSA) TDMA scheme,

an adaptive and dynamic TDMA slot scheduling model, where time slots are assigned to the sensor nodes on the fly, according to the need of the sensor nodes. The main goal of this study is to reduce the energy loss in the data transmission phase and minimize the wastage in channel bandwidth, in low activity networks with varying data traffic. We have presented the system model and the analytical model of the DSA MAC scheme. We have modeled the data traffic by a correlated stochastic process (i.e. Markov chain) for a network where the second and subsequent connection arrival rate is dependent on the first arrival rate. We have numerically compared our DSA model with a traditionally proposed static TDMA model, the Bit-Map-Assisted (BMA) model, and a variant of the BMA model (EA-TDMA), and have proved a substantial improvement in the energy consumption and channel utilization in low activity sensor networks. Results have showed that the efficiency of the MAC protocol can be increased significantly using the presented model.

- On top of the DSA MAC scheme, we have proposed Dynamic TDMA Slot Scheduling (DTSS) scheme, an adaptive and dynamic TDMA slot scheduling model, which can respond to the bursty traffic nature of a WSN by assigning multiple slots to a sensor node. It also reduces the wastage in channel bandwidth by utilizing the unused data slots, especially in low activity networks with varying data traffic. We have numerically compared the DTSS model with traditionally proposed static TDMA model, have proved a significant improvement in the bandwidth efficiency, and have shown a decrease in connection blocking probability in low activity networks. We have also investigated the weakness of the proposed system. Results have showed that the efficiency of the MAC layer protocol can be increased significantly using the proposed model with reasonably low packet dropping probability.

1.4 ***Organization of the Thesis***

The rest of the thesis is organized as follows. Chapter 2 gives details about the state of the art in the area of cluster-based WSNs. It covers a detailed survey on the related work done in the area of cluster-based routing protocols for WSN, reliability model for WSN

and energy efficient MAC layer protocols for low activity networks. Chapter 3 presents the BCH framework, with details of the protocol and the simulation results. Chapter 4 provides the network model and mathematical model of BCH algorithm based on the Markov chain model and shows its viability.

Chapter 5 presents the DSA protocol for TDMA-based MAC schemes. It also provides the system model and the analytical model of the DSA, and provides the numerical comparisons with existing work. Chapter 6 presents the enhancement of DSA with the proposal of DTSS model for low activity networks. Chapter 7 wraps up our thesis with conclusions reached in this work and the suggestions we proposed for future research.

1.5 **List of Publications**

- Shafiq U. Hashmi, J.H. Sarker, H.T. Mouftah, N.D. Georganas, “*An Efficient TDMA Scheme with Dynamic Slot Assignment in Clustered Wireless Sensor Networks*,” IEEE GLOBECOM '10, Florida, U.S.A., Dec 2010.
- Shafiq U. Hashmi, S.M.M. Rahman, H.T. Mouftah and N.D. Georganas, “*Reliability Model for Extending Cluster Lifetime using Backup Cluster Heads in Cluster-Based Wireless Sensor Networks*,” WiMob Workshop AWSAN '10, Niagara Falls, Canada, Oct 2010.
- Shafiq U. Hashmi, J.H. Sarker, H.T. Mouftah, N.D. Georganas, “*An Efficient MAC Protocol with Correlated Connection Arrival and Variable Slot Assignment in Wireless Sensor Networks*,” ICC '10, S. Africa, May 2010.
- Shafiq U. Hashmi, H.T. Mouftah, N.D. Georganas, “*Achieving Reliability Over Cluster-Based Wireless Sensor Networks Using Backup Cluster Heads*,” IEEE GLOBECOM '07, Washington DC, U.S.A., Nov 2007.
- Shafiq Hashmi, H.T. Mouftah, N.D. Georganas, “*A New Transport Layer Sensor Network Protocol*,” IEEE CCECE '04, Ottawa May 2006.
- Shafiq Hashmi, H.T. Mouftah, N.D. Georganas, “*Transport Layer Sensor Network Protocol – A review of issues and solutions*,” IEEE HONET 2005, Pakistan.
- Shafiq Hashmi, H.T. Mouftah. “*Integrated Optical/Wireless Networking, An Overview*” IEEE CCECE 2004, Niagara Falls, May 2004.

Chapter 2

Cluster-Based Wireless Sensor Networks - State of the Art

2.1 *Wireless Sensor Networks*

The advancements in Micro Electro-Mechanical Systems (MEMS) technology coupled with low power and highly integrated digital electronics enabled the emergence of inexpensive and low-power tiny devices, called micro-sensors. These sensors can be quickly deployed at low cost, thus enabling large-scale, on-demand monitoring and tracking over a wide area. It can be deployed where human access and monitoring is difficult, such as natural or man-made crises like severe weather, wild-fires, earthquakes, volcanic activities, chemical, biological or nuclear agents, structural and habitat monitoring. Even though, the sensing capability of an individual micro-sensor may be restricted in range and accuracy, cumulative detections from multiple micro-sensors will generate a reliable view of the environment. The wireless communication capability possessed by micro-sensors facilitates such coordination.

In a WSN (wireless sensor network), hundreds and thousands of tiny micro-sensors deployed in different scenarios, perform their respective sensing job and collect data. Due to the small size, low cost and lightweight of these sensor nodes, their deployment is incredibly effortless and less time consuming, like scattering in the sensing field or throwing from an aircraft. They are then self-organized in an ad hoc manner [AKY-02]. Figure 2.1 depicts a typical scenario of a wireless sensor network, where the sensor nodes

are spread in the sensor field. These sensor nodes gather the data and transport to the sink node or the BS (base station). External users at the sink node or BS may access these data via internet or satellite. The number of sink nodes can be multiple but they are far lesser than the sensor nodes.

The high number of sensor nodes enables the sensor network to have enough redundancy in the generated data to provide accuracy, even though a single micro-sensor is limited in sensing capability. Due to the same reason, wireless sensor networks are more fault-tolerant than traditional macro-sensor networks because failure of a single micro-sensor would not render the entire system useless.

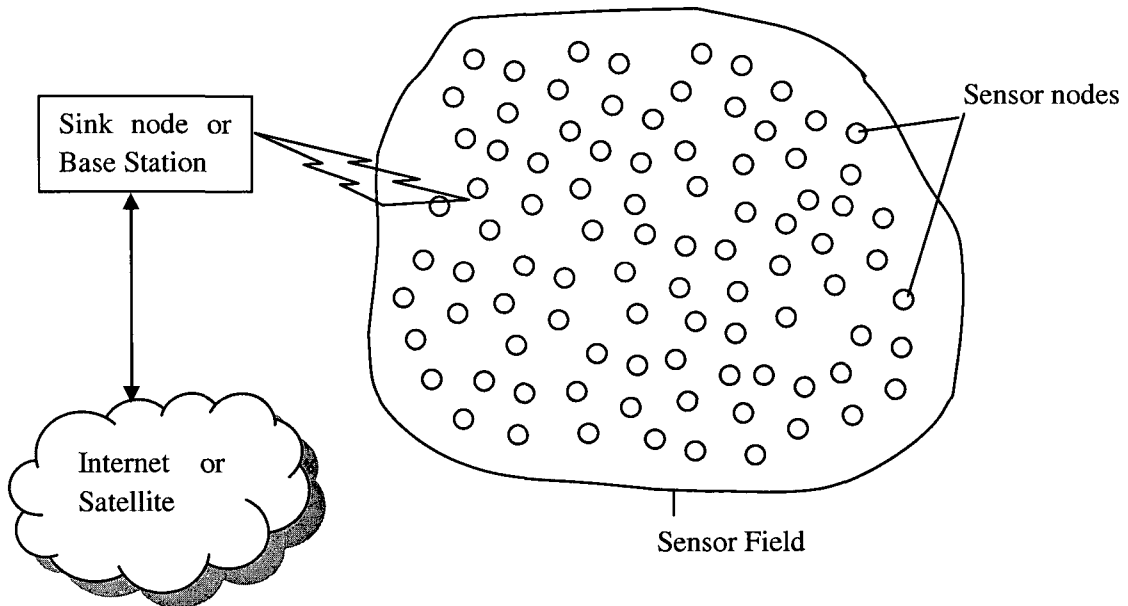


Figure 2.1: Typical scenario of wireless sensor network architecture

The wireless communication among the sensor nodes, gateways and sink nodes follows the same protocol stack as in traditional wireless communication. Long distance transmission necessitates the use of multi-hop relay due to short communication range of sensor nodes and constrained power supply. The communication protocol stack shared by all nodes, as illustrated in Figure 2.2, is proposed in [AKY-02]. The protocol stack includes the application layer, transport layer, network layer, data link layer, physical layer

as well as three planes. The functions of all the layers conform to the specification of the ISO Seven Layer model. Although here a layered architecture is shown, due to the application-related nature of WSNs, a cross-layer design (sharing information between layers) can achieve a better performance than an independent-layer design [HEI-00].

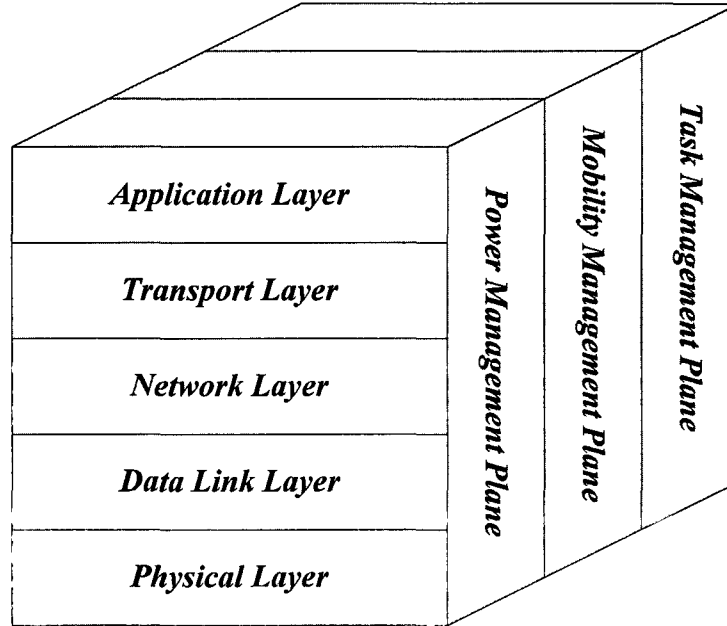


Figure 2.2: Wireless Sensor Network communication protocol stack

In addition, in the protocol stack, power, mobility and task management planes are added which are responsible for monitoring and providing the respective information to all the layers, so that these layers can exploit such information to optimize their operations. For example, the mobility management plane is responsible for detecting movement of neighbouring nodes and notifying the network layer, so that the routing table can be updated correspondingly. The power management plane is responsible for monitoring power usage of each sensor node. If the remaining power of a sensor node is going low, then its future activity should be carefully controlled. The task management plane is used to determine when a sensor node will partake into a sensing task. It can also be used to control nodes' communication activity. Not all of the sensor nodes may be ready to relay packets for others all the time. Some nodes may go into sleep mode to save energy and periodically wake up for sending and receiving packets.

2.2 ***Literature Review***

In this section, we review the algorithms and protocols that are related to our work. First, we discuss the cluster based two-tier sensor networks where our reliability work can be implemented, which provides the cluster reliability and data reliability. Second, we review the existing proposals for the reliability of cluster-based WSN. Then we present a survey of non-homogeneous Markov chain models used to model system reliability. The second portion of this review comprises the work done on TDMA-based MAC layer schemes. First, we discuss the protocols suggested for WSN employing TDMA MAC scheme. We then discuss the MAC layer proposals for low activity networks and for dynamic and adaptive TDMA time slot scheduling.

2.2.1 **Hierarchical-Based Routing Protocols in Wireless Sensor Networks**

The hierarchical-based routing protocols have been widely pursued by the research community due to its inherent network scalability property [ALK-04]. In this routing methodology, the sensor nodes are grouped into clusters. For every cluster a leader is selected which is usually referred as the CH (Cluster-Head) of the cluster. The CH may be elected by the sensor nodes in a cluster or may be pre-assigned by the network designer or a BS (base station). The CH may be like a normal sensor or may be a node that is richer in resources as compared to the other sensor nodes. The cluster membership may be permanent or temporary.

Along with network scalability, clustering has several advantages. It localizes the route set up within the cluster, thus reduces the size of the routing table stored at the individual node, and hence conserves its scarce memory [AKK-05]. Clustering also conserves communication bandwidth since it limits the scope of inter-cluster interactions to the CHs only and avoids redundant exchange of messages among the sensor nodes [YOU-03]. Moreover, clustering stabilizes the network topology at the level of sensor nodes and thus cuts on topology maintenance overhead. The CH may also employ optimized management strategies to further improve the network operation and extend the battery life of the individual sensor nodes and the network lifetime [YOU-03]. The CH can schedule

activities in the cluster so that the sensor nodes can sleep and wake-up accordingly and hence save the energy. Furthermore, the CH may also aggregate the data collected by the sensor nodes in its cluster and thus decrease the number of relayed packets [HEI-02]. In [ABB-07] a wide survey is given regarding the clustering algorithms for WSN and their attributes.

[HEI-00] proposed one of the earliest cluster-based protocol for wireless sensor networks called LEACH (Low-Energy Adaptive Clustering Hierarchy). The idea of LEACH is to divide the system operation timeline into fixed intervals (rounds). In each round, each sensor node determines its role in a cluster, as CH or non-CH, based on its duty in previous rounds. Data collection starts from each non-CH sending its data to its CH. Then CHs aggregate all data reports received and send the compressed result directly to the BS. In LEACH, the role of the CH is rotated among all sensor nodes to prevent energy draining of a single node. There is another variation of LEACH, which is named as LEACH-C. In this scheme, the cluster formation and the CH selection is centralized and done by the BS, after getting all the information of the sensor nodes at every round. However, LEACH is based on the assumption that each node in the network can directly communicate with each other node. Therefore, it is not scalable for large-region networks.

Many other researchers motivated by the idea of LEACH to develop hierarchical routing protocol. TEEN (Threshold sensitive Energy Efficient sensor Network protocol), proposed by [MAN-01] is one of them which is designed for time-critical applications, in which quick response is an important metric for protocol performance. However, two thresholds (soft or hard) are broadcasted to nodes to trigger their data transmission. TEEN does not work well for those applications where periodic data collections are needed since sink node may not get any data if the thresholds are not reached. Later Manjeshwar et al proposed APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol) by combining data collection strategies in LEACH and TEEN [MAN-02] [MAN-02a]. In other words, APTEEN is a hybrid protocol that lets the sensor nodes send reports periodically and immediately respond to sudden environmental changes whenever their sensed data exceed some threshold values.

In [LIU-04], Liu et al modified LEACH to support networks where nodes have mobile

capability and proposed Clustering with Mobility (CM) protocol. First, in clustering formation phase, the algorithm predicts the distance of two nodes in the future and assigns each non-CH to the CH, which may have a minimal distance to the concerned node. Second, Liu et al observed that LEACH suffers from significant energy consumption when there are no CHs selected in some rounds. They provided two approaches to avoid this situation. One is to skip the round, in which no CH is elected. The other is to count and fix the CH number in each round. In [BAJ-08], Bajaber et al also extended LEACH-Centralized and proposed Dynamic/Static Clustering protocol (DSC). They kept the clusters' setup fixed for every 10 rounds. They proved that the DSC provides better performance than LEACH-C in terms of communication overhead, network lifetime and energy dissipation over time.

In [CHO-08] Jin et al presented a clustering method of enhanced tree establishment that constructs a tree structure for optimized energy consumption. The parent node is selected by a minimum summation of the distances of current-parent CH and parent-grandparent CH in the candidate list and this establishes the tree structure. The method consists of three stages, cluster construction, tree establishment and the data transmission. This protocol is energy efficient, as in order to optimize the distance it constructs the tree structure between the CHs.

In [BAN-03], Bandyopadhyay et al proposed to organize the sensor nodes into a multiple-layered clustering architecture for data collection. The most impressive part of their work is that they derived an optimal value of the clusters' number at each layer and hop number in each cluster in order to minimize the total energy cost for data collection.

In [YE-02], Ye et al described different kind of hierarchical data dissemination protocol for WSNs. This protocol consists of two-tiers and aims to enable mobile sink nodes to receive data continuously. Data dissemination starts from a source node actively building a grid-structure once it detects a stimulus. The protocol assumes that the sensor nodes are stationary and location-aware. Therefore, each source node can maintain the grid-structure with a little cost. With the grid structure in place, query flooding is restricted in the local grid cell where the sink node is located. Once the query reaches a sensor node located at the backbone of the grid-structure, it follows the grid structure upstream to the

source node, pulling its data back to the sink node. As long as the sink node does not move out of the cell, it can continue to receive data without any stop.

[PAN-03] also proposed a two-tiered architecture for WSNs with resourceful access nodes (AN) and many low-cost sensor nodes forming clusters. Their aim is to provide topology control for WSN by focusing on the distance-dominated communication-related power consumption in WSN and maximizing the topological lifetime of WSN.

In [HOU-03], Hou et al proposed the Smart Energy Exploitation and Sharing (SEES) algorithm, which is a single-session routing solution. Like in [PAN-03], their goal is also to maximize the network lifetime, but by using the optimal flow routing through power control among the upper-tier CHs, which they call AFN (Aggregation and Forwarding Nodes). Kim et al proposed another two-tiered data dissemination protocol SAFE (Sinks Accessing data From Environments) that aims to save the energy through data dissemination path sharing among multiple data sinks [KIM-03]. Here individual sensor observations are disseminated to data sinks, which explicitly present their interests by sending the data requests. SAFE provides energy efficiency and fast response, without severe degradation, as the number of data sources and data sinks increases.

Another protocol, Hybrid Energy-Efficient Distributed clustering for ad hoc sensor networks (HEED) is presented in [YOU-04]. It periodically selects the CHs according to a hybrid of the node residual energy and a secondary parameter, such as node proximity to its neighbours or node degree without any assumption about the presence of infrastructure or node capabilities.

In [SUB-10], Kalyan et al proposed a Selective Flooding-based Routing Protocol (SFRP) for multi-hop routing in clustered WSN. SFRP is specifically targeted at environmental monitoring applications using a limited flooding mechanism. They suggested forming a tree structure of the CHs with a parent-child relationship among the CHs, facilitating the routing to the sink through the CHs. They avoided the traditional flooding of route discoveries by selective flooding of the routing packets to the appropriate sensor nodes, thereby saving energy of the remaining nodes.

Youssef et al [YOU-06] suggested that guaranteeing some degree of overlap among the clusters could facilitate many applications like inter-cluster routing, topology discovery

and node localization, recovery from the CH failure, etc. They proposed a randomized, distributed Multi-hop Overlapping Clustering Algorithm (MOCA) for organizing the sensor nodes into overlapping clusters. The goal of the clustering method is to guarantee that each node either is a CH or is within k hops from at least one CH, where k is a preset cluster radius. The algorithm allows each sensor node in the network to become a CH with a certain nomination probability. Each CH then sends its advertisement to the sensor nodes within its radio range, which is then forwarded to all the sensor nodes that are no more than k hops away from the CH. The sensor nodes in reply send a request to all CHs that it heard from in order to join their clusters. In the join request, the node includes the ID of all the CHs it heard from, which implicitly means that it is a boundary node.

2.2.2 Reliability and Fault Tolerance in Cluster-Based Wireless Sensor Networks

The protocols we discussed yet do not address the situation when the CH nodes die at any point rendering the data loss. However, there are a few works that provide some reliability and fault tolerance in the cluster-based networks. The authors of [GUP-03] provided fault tolerance by introducing a few powerful gateway nodes into the clusters, to organize the tiny sensor nodes. However, because these gateway nodes take a critical role in the network, the system is more sensitive to failure of any of them. Therefore, they enhanced the existing cluster-based data collection approach such as LEACH by quickly detecting a failed gateway node and assigning its members to other alive-nodes. This method enables the region to get the coverage back, but reassigns the sensor nodes to other existing gateway, which increases the load on those gateways. In addition, this method uses heterogeneous sensor networks that uses specialized CH gateways and cannot be applicable to those cluster-based protocols where the CHs are rotated.

[KAR-10] presents a hybrid routing protocol based on Rapid Spanning Tree Protocol (RSTP) for CH routing. The authors took into consideration the tasks of the CHs that a CH not only collects the data from the sensing nodes of its cluster but also relays the collected data from other CHs. This leads to a non-uniform traffic distribution in different clusters of the WSN. The CHs closer to the sink relay more traffic than those located at farther region and hence collapsed earlier. The suggested protocol does the clustering by

partitioning the multi-hop network and then chooses its CHs. Then all the CHs construct a Rapid Spanning Tree (RST) to prolong the network lifetime, save energy and shorten the routing path. The proposed protocol provides faster spanning tree convergence after a topology change, thereby minimizing the energy consumed. It also provides some cluster stability because when the energy of a CH is lower than a threshold, the CH switches its role with a sensor node within the cluster having the highest residual energy and becomes a normal sensor node.

In [DON-08] Yunquan et al proposed Priority-based Energy Aware and Coverage Preserving (PBEACP) routing protocol. For the selection of the CH, along with the remaining energy, they also considered the node's geographic distribution and sensing intensity which lead to an even distribution of the energy consumption among the sensor nodes. It also improves the sensing coverage of the CH, even if the topology of the network changes when there are nodes running out of energy. However, it could not provide a solution for the case when a CH dies, until the new round. [HAO-04] provided the fault tolerance to a cluster-based two-tier network. They formulated an optimization problem called 2-Connected Relay Node Double Cover (2CRNDC), to place a minimum number of backup relay node for every sensor nodes. So, if any relay node fails, the sensor nodes will still be covered by backup relay node.

Boukerche et al provided a fault tolerant cluster-based network for inter-cluster communication [BOU-07]. They proposed an energy efficient inter-cluster communication based routing protocol for WSNs that employs the redundant backup path for routing. They achieved the fault tolerance by keeping two sensor nodes as responsible for inter-cluster communication. If any node between the two sensor nodes dies, the other one takes over. The algorithm creates multiple paths, if one of these paths has faulty nodes, the other ones will be used for the event notification's propagation in the opposite direction. If there is a broken path somewhere along the source-sink route, it will be found out when the message is not acknowledged to the sender sensor node.

In [HUS-06], Sajid et al proposed a BS assisted cluster-based routing, where BS determines the number of clusters and a set of CH members. In every round, each cluster has a number of sensor nodes and a small number of headsets that will take the

responsibility of CH one-by-one. Therefore, the overhead of cluster forming after every few frames is reduced. However, these headsets do not work as a backup to the current CH. In [ZHE-06], the authors proposed an Energy-Efficient Redundant Nodes Tree (EERNT) mechanism in which the redundant nodes in each cluster can be used to relay information to the BS. The principle is that the redundant nodes relay tree is constructed according to the position of the redundant nodes and all the information received by the CHs is sent to the closest redundant node of the EERNT. The selected redundant node transmits the information to the BS via other redundant nodes. References [HUS-06] and [ZHE-06] do talk about some redundant CH in a cluster, but fail to cover the data backup aspect.

The authors of [CAP-09] proposed an architecture EDETA (Energy-efficient aDaptive hiErarchical and robuT Architecture) which provides fault tolerance among other features. They noticed that if a CH fails, all the sensor nodes in the cluster are not able to send its data. They introduced a substitute node within the cluster that shares the schedule with the CH and takes its place if it fails. The substitute node is selected by the CH in the setup phase, based on the sensor node's energy and the proximity between them. This substitute node keeps monitoring its CH's operation and when the CH fails, it would detect that the CH is no longer responding its messages, and it would take its place, acting as the CH. This idea is very similar to our work [HAS-07] but published two years after us.

Demirbas et al proposed Fast LOcal Clustering service (FLOC) in [DEM-04]. FLOC is a distributed technique that produces approximately equal-sized clusters with minimum over-lap. They assumed a radio model which classifies the sensor nodes based on their proximity to the CH into inner (i-band) and outer (o-band) bands. I-band nodes suffer very little interference while communicating with the CH, where as the messages from o-band nodes may get lost. For FLOC, the authors proposed a self-healing method for the CH failures by employing heartbeats, which enables the members to detect the failure of the CH. The CH periodically broadcasts a message. If a node j fails to receive the heart-beat from its CH within certain duration, then the node j dissociates itself from the cluster. It waits for a specified period so that all the members may detect the failure of the CH. Then either the dissolved members join the neighbouring clusters as o-band members or an

eligible candidate unites these nodes in a new cluster within some time.

The authors of [KAR-09] proposed an energy-efficient and Fault Tolerant Dynamic Static Clustering (FT-DSC) protocol for WSN to enhance the performance of DSC [BAJ-08]. They used the hello/ACK messages at the end of the round between CH and BS, by which the BS is able to detect the failure of CHs. Also, the CH and/or BS subscribes to non-CH nodes of a cluster to notify only when an event of interest occurs. In this way, the non-CH nodes do not send data to CH in every time slot of a frame allocated to them, which reduces energy consumptions. The authors of HEED [YOU-04] also gave a solution for CH failure and proposed to construct multiple (say k) node-disjoint overlays of CHs, assuming node density allows this. This enables to construct the k -connected graphs, where k is an environment-dependent constant specified by the application.

Ataul Bari et al in [BAR-07] investigated the problem of appropriately placing relay nodes in a sensing area, in order to maintain network connectivity and desired coverage of all the sensor nodes along with fault tolerance to sensor node failures. They proposed integer linear programming (ILP) formulation for the optimal placement of the relay nodes in a specified sensing area to ensure each sensor node is covered by at least one relay node. They later extended this initial formulation to incorporate fault-tolerance, by requiring that each sensor node is covered by a specified number of relay nodes k_s , and the relay node network itself has a connectivity of at least k_r nodes. This ensures that each sensor node can still transmit its data to at least one relay node, even if up to $k_s - 1$ relay nodes fail. Similarly, it guarantees that each relay node has an available path to the base station, even if up to $k_r - 1$ relay nodes fail.

In [MEH-10], the authors proposed FEED (Fault tolerant, Energy Efficient, Distributed clustering) where in each cluster among the sensor nodes they selected a CH, a pivot CH (PCH) and a supervisor node (SN). The CH node is a regular CH, which is the head of its cluster. The PCH node has more resources and added capabilities as compared to the CH. All the PCH nodes of the network cover a big area of the entire network and act as routers. SN is the supervisor node for its cluster heads (CH or PCH) and replaces its CH or PCH in the event anyone of them fails. So, SNs are substitutes for their CHs which try to achieve a fault tolerant clustered network. The proposed scheme here applies the same principle that

we had proposed three years earlier in [HAS-07].

Table 2.1 gives a summary of the proposed routing protocols for cluster-based WSNs that we have mentioned in this chapter.

Table 2.1: Comparison Table for Cluster-Based WSN

Clustering Protocols	Energy Efficient	Fault Tolerance	Cluster Maintainability	CH Type	Clustering Methodology	Inter-cluster connectivity	Mobility
LEACH	Yes	No	No	Sensor	Distributed	Direct Link	No
LEACH-C	Yes	No	No	Sensor	Centralized	Direct Link	No
TEEN	Yes	No	No	Sensor	Distributed	Direct Link	No
CM	Yes	No	No	Sensor	Distributed	Direct Link	Yes
DSC	Yes	No	No	Sensor	Centralized	Direct Link	No
[CHO-08]	Yes	No	No	Sensor	Distributed	Multi-hop	No
[BAN-03]	Yes	No	No	Sensor	Distributed	Multi-hop	No
[PAN-03]	Yes	No	No	Resourceful	Distributed	Multi-hop	No
2CRNDC	No	Yes	No	Sensor	N/A	Multi-hop	No
SEES	Yes	No	No	Sensor	N/A	Multi-hop	No
HEED	Yes	Yes	No	Sensor	Distributed	Multi-hop	No
SFRP	Yes	No	No	Sensor	Distributed	Multi-hop	No
RST-CHR	Yes	No	Yes	Sensor	Distributed	Multi-hop	No
MOCA	No	Yes	No	Sensor	Distributed	Multi-hop	No
[GUP-03]	No	Yes	No	Resourceful	Centralized	Multi-hop	No
PBEACP	Yes	No	No	Sensor	Distributed	Direct Link	No
[BOU-07]	Yes	Yes	No	Sensor	Distributed	Multi-hop	No
[HUS-06]	Yes	No	No	Sensor	Centralized	Direct Link	No
EERNT	Yes	No	No	Sensor	N/A	Multi-hop	No
EDETA	Yes	Yes	Yes	Sensor	Distributed	Direct Link	No
FLOC	Yes	Yes	No	Sensor	Distributed	N/A	No
FT-DSC	Yes	Yes	No	Sensor	Centralized	Direct Link	No
[BAR-07]	Yes	Yes	No	Sensor	Distributed	Multi-hop	No
FEED	Yes	Yes	Yes	Sensor	Distributed	Direct Link	No

2.2.3 Reliability Models Based on Markov Chain Models

Several works have been proposed to model the reliability and survivability of WSN. Dong et al in [DON-06] proposed the survivability model by adopting rejuvenation methodology. They analyzed each cluster of a hierarchical cluster-based WSN as a stochastic process based on a Semi-Markov Process (SMP) and a Discrete-Time Markov Chain (DTMC). They proved that their model could extenuate the failure probability and increase the probability of the system staying in a healthy state.

Vasar et al in [VAS-09] did the reliability analysis of the WSNs with Markov models. They suggested that a better reliability of the entire system could be achieved by either improving the quality of the components or by increasing the number of available replacements. They compared the two approaches based on the criteria of cost indicators and Mean Time To Failure (MTTF) factor, and concluded that the optimal choice is to use a high number of universal replacements.

In [SHA-08], Elhadi et al proposed a fault inference mechanism based on reverse multicast tree to evaluate sensor nodes' fault probabilities to provide high stability and availability of large-scale sensor networks. They modeled this inference mechanism as Markov process and adopted Chapman-Kolmogorov functional equations to compute fault probabilities of nodes.

Paulo et al presented Markovian Models for medical signals in WSN [SAL-09]. They proposed two different Markovian models, the Markov Modulated Poisson Process (MMPP) and the Markov Modulated Deterministic Process (MMDP), to model the signal generated by a single sensor node monitoring ElectroEncephaloGram (EEG) data. They proved that the first model is appropriate for modeling the EEG signals, as the sensor nodes used for medical applications employ source coding to reduce the amount of data that must be transmitted, thus conserving energy. The second model is found more suitable to describe the signal power that is used to transmit the encoded EEG signal.

[THE-09] developed a framework for secure and survivable WSN that can provide essential services in the presence of attacks and failures, and recovery of full services in a timely manner. They proposed a framework of survivability model using Markov chains

with rejuvenation methodologies for WSNs.

In the domain of ad hoc wireless networks, Al-kahtani et al [ALK-05] proposed a stable clustering formation infrastructure protocol by electing primary and secondary CHs (PCH and SCH respectively) for each cluster. They modeled the cluster behaviour by Markov chain with homogeneous transition probabilities and ergodic Markov chain properties.

Markov transition models are also used to model disease progression. Three-state non-homogeneous Markov models are often found in the modeling of progression of chronic diseases like cancer, with one absorbing state, 'death'. In [AND-91], Andersen et al presented one such model. The proposed model can be formulated and analyzed in situations where the main event of interest is, for instance, the death of the individuals under study and where there are one or few discrete, time-dependent covariates recording e.g., the occurrence of possibly recurrent events. They used a non-homogeneous Markov process with one absorbing state (death) and a transient state (alive) for each value of a single discrete time-dependent covariate or for each combination of values of several such covariates.

Hsieh et al in [HSI-02] also assessed a chronic disease progression and proposed two non-homogeneous models using the Weibull distribution and piecewise exponential model, together with covariate functions of the proportional hazard form. They showed that the proposed non-homogeneous Markov models could be easily applied to the rates of progression of chronic disease with increasing or decreasing rates with time.

Z. Uhry et al presented an overview of Markov models in cancer screening evaluation and provided two specific models [UHR-10]. First, they proposed a three-state model to estimate jointly the sensitivity of the screening procedure and the average duration in the preclinical phase. Later they proposed a five-state model, incorporating lymph node involvement as a prognostic factor, combined with a survival analysis to predict the mortality reduction associated with screening. They illustrated the strengths and limitations of these two models and concluded that the three-state model is a useful model but the parameter estimates should be interpreted with caution. Whereas, in the case of five-state model, they pointed out a serious limitation due to the implicit assumptions

which are not always verified.

Authors of [HUI-04] developed a SAS (*Statistical Analysis System*) macro program for modeling and estimating the transition parameters in multi-state disease process, particularly non-homogeneous models, using SAS/IML (*Statistical Analysis System/interactive matrix language*) procedure. They successfully applied the program to an example of a three-state disease model for the progression of colorectal cancer from normal (disease free), to adenoma (pre-invasive disease), and finally to invasive carcinoma, with or without adjusting for covariates. The authors claim that the developed macro program can be generalized to other k -state models with s covariates.

In [WEL-05], Welton et al showed that the solution to Kolmogorov's forward equations could be exploited to map between transition rates and probabilities from probability data in multistate models. The authors showed that how underlying transition rates could be recovered from partially observed data using Markov chain Monte Carlo methods in WinBUGS (Bayesian inference Using Gibbs Sampling for Windows) software. They suggested diagnostics to investigate inconsistencies between evidences from different starting states. They gave a 3-state model as an illustrative example, where they showed how the given methods were extended to complex Markov models using the software WBDiff (WinBUGS Differential Interfere) to compute solutions. In [OCA-05] Ricardo also reviewed the methods for fitting non-homogeneous Markov models. He proposed an algorithm for biomedical data analysis and applied the method to analyze breast cancer data. The data are modeled by a three-state Markov process with two transient states ('With symptoms' and 'Without symptoms') and one absorbing state (Death).

Many others employed non-homogeneous Markov chain models in biomedical sciences in order to study the disease history events and disease progression. Interested readers may refer to [PER-00], [FRY-95], [SUN-07] and [CHE-07] to have further insight of its applications.

2.2.4 TDMA-Based MAC Layer Protocols for Wireless Sensor Networks

WSNs are task-based and data-centric, where the sensor nodes gather the data and send them to a gateway (or a BS) either periodically or in response to a query request or at the occurrence of events. This data flow shapes different traffic types throughout the network. To handle the channel access based on the traffic type, many Media Access Control (MAC) protocols have been proposed. Mainly, they can be divided into contention-based MAC protocols and Time-Division Multiple-Access (TDMA) based MAC protocols [CZA-06]. There are also FDMA (Frequency Division) and CDMA (Code Division) techniques but they require complex hardware and have high computational demands. Although in few works, TDMA-based MAC protocols that are used for clustered WSN, use Direct-Sequence Spread Spectrum (DS-SS) based CDMA codes for channel usage to avoid inter-cluster interference [CIO-08].

The contention-based protocols, based on CSMA/CA, permit nodes to access the shared wireless channel independently [CZA-06], [GOB-09]. These are simple, flexible, and robust protocols where nodes are not required to form clusters. These protocols are scalable, and they do support dynamic nodes joining and leaving. During light traffic, these protocols behave efficiently, however, when there is heavy traffic and high event occurrences, then contention-based MAC protocols fail to respond efficiently. These cause collisions leading to lower throughput, higher latencies and higher energy consumption, which is lethal for WSNs [GOB-09].

TDMA-based MAC protocols perform better in high traffic load [CIO-08]. TDMA allows every sensor node to transmit its own data eventually. The sensor nodes are assigned their own time slot and they access the shared medium only in this time slot. They transmit data in a round robin fashion and thus avoid collisions. However, during the light traffic when every sensor node does not have data to send, the bandwidth and the energy is wasted. There are other benefits and shortcomings of contention based and TDMA based MAC schemes that could be looked in [CZA-06] [SAR-02]. There are also Hybrid MAC algorithms that take the advantages of both categories and attempt to resolve their drawbacks [BAC-10].

There are several suggested solutions for the MAC layer protocol using TDMA mechanism. Heinzelman et al were one of the first to propose a TDMA-based protocol in WSNs [HEI-00]. Their proposed protocol, Low-Energy Adaptive Clustering Hierarchy (LEACH), is a self-organizing adaptive clustering protocol that uses randomization to distribute the energy load evenly among all the sensor nodes in the network. LEACH is an application specific protocol that combines clustering and data fusion to save energy, employing TDMA schedule to coordinate nodes' access to the available channel. Hybrid Energy-Efficient Distributed protocol (HEED) [7] is another such protocol that uses the classic TDMA model. These protocols consider 100% network activity, and assume there is constant event occurring.

The Time Synchronized Mesh Protocol (TSMP) is designed for the recently ratified Wireless HART (Highway Addressable Remote Transducer) standard (an open-standard wireless networking technology) in industrial automation [PIS-08]. It enables reliable, low power, secure communication in a managed wireless mesh network. It is a TDMA-based protocol where access is controlled by means of a tuneable amount of time slots which form a frame. TSMP enables the participation of a node in multiple frames at once allowing it to have multiple refresh rates for different tasks. The authors showed that with the 802.15.4 physical layer and 10 ms time slots, TSMP can theoretically achieve a secure payload throughput of 76 kbps at a single egress point.

In [ARI-02], Arisha et al presented an energy aware management of sensor networks that maximizes the lifetime of the sensor nodes while maintaining desired quality of service attributes related to sensed data delivery. Here the sink node gathers the topology information about the network topology and assigns time slots to all the nodes accordingly. The authors proposed an algorithm to compute the scheduling table where the slot assignment can be done according to a breadth first search or a depth first search. However, the proposed mechanism is not scalable.

Sinem et al proposed PEDAMACS (Power Efficient and Delay Aware Medium Access Control protocol for Sensor networks) in [COL-06], where the BS/access point gathers information about the traffic and topology during the setup phase. During the topology learning phase, each node discovers its neighbours, its interferers, and its parent node in a

shortest-path tree rooted at the BS. Then comes topology collection phase which is based on CSMA where sensor nodes send this (local) topology information to the BS, so at the end of this phase, the BS knows the full network topology. The BS then establishes the TDMA scheme for the uplink communications. The collision-free scheduling is based on coloring the original conflict graph.

μ MAC is presented by Barroso et al in [BAR-05] which relies on external clock synchronization based on a beacon source. The communication channel in μ MAC is divided into a contention period for two-hop topology construction and a contention-free period for data exchange. The contention period is also slotted. During this period, nodes transmit packets in slots. As there are no acknowledgments, retransmissions ensure reliability.

PACT (Power Aware Clustered TDMA) adopts the duty cycle to the user traffic by turning off the radio if the network is inactive [PEI-01]. It employs passive clustering to take advantage of the redundant dense topology and prolong the lifetime of the entire network even further. At any given time, only a subset of network nodes and CHs participate in the communication. The TDMA frame begins with mini-slots used for exchanging control information. The remainder of the frame contains the transmission slots for the sensor nodes according to the schedule.

In [LEE-06], Winnie et al proposed FlexiMAC (Flexible MAC), a TDMA-based protocol for efficient data gathering in WSNs. FlexiMAC designed a synchronized and flexible slot structure in which nodes in the network can build, modify, or extend their scheduled number of slots during execution, based on their local information. FlexiMAC is a fault tolerant and an energy efficient scheme, which minimizes the energy consumption by selecting the optimum node transmission-power for a given topology. FlexiMAC allows communication slots to be reused by nodes outside each others' interference range which makes it scalable for large number of sensor nodes. Its depth-first-search schedule also minimizes buffering.

Hoesel et al presented Lightweight Medium Access Control protocol (LMAC), a TDMA-based energy-efficient MAC protocol which self-organizes the network, in terms of time slot assignment and synchronization, based upon local information only [HOE-

04a]. The main goal of this medium access protocol is to minimize the overhead of the physical layer. The protocol reduces the number of transceiver state switches and hence saves the energy wasted in preamble transmissions. AI-LMAC (Adaptive Information-centric Lightweight MAC) [CHA-04] enhanced LMAC and proposed that each node may access more than one slot. AI-LMAC is application dependent as it adapts its operation depending on the type of query injected into the network and also the type of data that flows through it. The protocol provides a data management framework that helps gather data about the queries and how it is subsequently used by the MAC layer to adjust its operation.

Incel et al proposed Multichannel LMAC [INC-06] to enhance the TDMA-based LMAC with multi-channel support. When the density of the network goes very high, all the times slots end up assigned, and the new sensor nodes may end up without a time slot thus unable to communicate. Incel et al proposed for those nodes to pick a slot on another frequency. In effect, they roughly multiplied the number of potential slots by the number of frequency channels. This protocol hence enables more nodes to communicate in LMAC.

In [KUL-06], Kulkarni et al designed SS-TDMA (Self-Stabilizing TDMA), a TDMA service for a grid-based sensor network, considering three communication patterns: broadcast, convergecast, and local gossip. Their TDMA service can be customized based on the application requirements and can provide guidance about using this service when the communication pattern is unknown or varies with time. These customizations enable a sensor to forward the messages it received to its successors with a small delay. Their proposed service can also be used on a 2-D field, failure of the sensor nodes, and in a mobile sensor network, that provides a localization service.

In [SHI-10] Liqi et al, provided network-wide optimized TDMA schedules that can achieve high power efficiency, zero conflict, and reduced end-to-end delay. They built a nonlinear cross-layer optimization model involving the network MAC and physical layers, which aims at reducing the overall energy consumption. To solve this nonlinear cross-layer optimization model, they transformed it into two simpler sub problems. They also proposed an algorithm for deriving the TDMA schedules, utilizing the slot reuse concept

to achieve minimum TDMA frame length, based on the network-wide flow distribution calculated from the optimization model and transmission power on every link.

[DIA-10] proposed a distributed TDMA scheduling protocol specifically designed for data aggregation, called RandSched. The protocol checks if the transmissions of different sets of nodes succeed simultaneously or not through a lightweight contention process. It then assigns the same slot to them if they have been proved to tolerate each other's interference. The authors proved by simulation that RandSched obtains a collision-free schedule by constructing and testing the schedule incrementally.

[NAB-10] proposed MCMAC (Mobile Cluster MAC) for supporting mobile clusters in WSNs. As it was designed for body area networks, therefore they mimicked the behaviour of cluster movement for the mobility model. It showed better application level latency and reliability as compared to the given protocols. Authors also proposed optimization methods that decrease the power consumption overhead without worsening the latency.

In [SHA-10], Shanti et al presented an integrated TDMA-based MAC and routing protocol called Delay Guaranteed Routing and MAC (DGRAM) for delay sensitive WSN applications. DGRAM provides deterministic delay guarantee with reduced latency. It reuses the TDMA slots and ensures that the medium access is contention free. The authors carefully computed the transmission and reception slots of the sensor nodes, and provided a detailed design of time slot assignment and delay analysis of the protocol.

2.2.5 TDMA-Based Dynamic MAC Layer Protocols

Here we present the TDMA-based MAC layer protocols for WSN which are designed for varying network traffic. Some proposed to assign the TDMA time slot to the sensor nodes dynamically while others avoided assigning any time slot when the sensor nodes have no data.

Jing et al proposed the Bit-Map-Assisted (BMA) MAC protocol [LI-04], which is intended for event-driven applications, where sensor nodes transmit data to the CH, only if significant events are observed. It reduces the energy wastes due to idle listening in low activity network. BMA in every frame schedules the TDMA slots for only active sensor nodes by introducing a contention period before the frames. But BMA keeps the same

frame size, keeping an idle period in the frame for inactive sensor nodes, which wastes the bandwidth.

Researchers who proposed MAC protocols for event-driven applications tried to improve energy consumption and bandwidth utilization of BMA [SHA-08], [BAR-07], [XIE-08], [FAN-07]. Shafiullah et al [SHA-08] proposed EA-TDMA (Energy-efficient adaptive TDMA) where they removed the contention window of BMA and had the CH listen to the channel at the beginning of every slot and go in sleep mode if no activity is found. Authors of [BAR-07] and [XIE-08] tried to improve the bandwidth efficiency of BMA by avoiding the idle period from the frames. Fan et al [FAN-07] employed famous token ring methodology in the MAC layer protocol for WSN.

Hussain et al in [HUS-09] proposed LASA (Low-energy Adaptive Slot Allocation), changing the fixed slot size in traditional TDMA schemes by a variable slot size that dynamically adapts to the data size generated at sensor nodes. Their scheme removes idle slot time when nodes remain unnecessarily active with no data to transmit or receive. TDMA-ASAP (TDMA-Adaptive Slot-stealing And Parallelism) is presented in [GOB-09] with some modifications to traditional TDMA that allows for the same efficiency of TDMA, while allowing the network to preserve energy during times of low network activity. Among other features, they proposed a judicious and controlled TDMA slot stealing procedure in order to use the empty slots.

Kumar et al [KUM-08] addressed differentiated data delivery in the presence of congestion due to burst data traffic in WSNs. Along with Congestion-Aware Routing (CAR), they proposed MAC-Enhanced CAR (MCAR) which includes MAC-layer enhancements and a protocol for forming high-priority paths on the fly for each burst of data. MCAR effectively handles the mobility of high-priority data burst, at the cost of degrading the performance of low-priority traffic.

The BitMAC protocol [RIN-05] is based on spanning tree of the WSN with the BS at the root. In this tree, every internal node and its direct children build a star topology network. Overall, the tree is composed of a number of interconnected stars. Within each star, TDMA is used to avoid interference among the children while sending the data to the parent and the time slots are allocated on demand to the sensor nodes that actually need to

send the data. By means of a distributed graph-coloring algorithm, different channels are assigned to neighbouring stars as in order to avoid interference between them. Both the setup phase and the actual data transmission phase are deterministic and free of collisions.

In [BRO-06], Brownfield et al proposed energy adaptive WSN MAC protocol, Gateway MAC (G-MAC), which implemented a new cluster-centric paradigm to effectively distribute cluster energy resources and extend network lifetime. Every TDMA frame of G-MAC starts with the collection period, in which nodes contend for the channel and send packets expressing their future upload traffic. Then in distribution period, all nodes wake up and receive the Gateway Traffic Indication Message (GTIM). In GTIM, the gateway declares the current time, the next collection period, the next distribution period, and the schedule of message transactions between cluster nodes. Then the contention-free period starts where the sensor nodes having data, send their data according to the schedule.

Katayoun Sohrabi et al presented SMACS (Self-organizing Medium Access Control for Sensor networks), an infrastructure building protocol that forms a single-tier flat topology for WSN [SOH-00]. SMACS is localized and distributed, that is, there is no need for a master node. They have combined the neighbour discovery phase with channel assignment phase in the SMACS protocol. They assign a channel to a link on the fly, immediately after the existence of the link is discovered. This way links between the sensor nodes begin to form concurrently throughout the network. By the time, all nodes hear all their neighbours; they will have formed a connected network.

In [RAJ-03], the authors presented TRAMA (TRaffic Adaptive Medium Access protocol) that determines a collision-free scheduling and performs link assignment according to the expected traffic. The protocol starts with localized topology formation and then creates a scheduled channel access. The scheduled channel access allows each node to wake up, only to transmit or to receive, which reduces idle listening and overhearing to zero. Using traffic information, TRAMA avoids assigning time slots to nodes with no traffic to send. The same authors then presented FLAMA (FLOW-Aware Medium Access) in [RAJ-05], an improvement to TRAMA by avoiding periodic exchange of information between two-hop neighbours.

EMACs (Energy Efficient MAC), given in [HOE-04], has three modes of operation: active, passive and dormant mode. The sensor nodes participate in communication only in active and passive modes, while the sensor nodes in dormant mode stay inactive due to depleted energy. Unlike traditional TDMA, the time slots in EMACs are not divided among the networking nodes by a central manager. Instead, the sensor nodes can autonomously pick time slots with local network topology knowledge. PMAC (Position-enabled MAC), like EMACs, defines three types of nodes: dynamic, passive and sleep node [CHE-05]. It adds a new period in the slot structure to enable the sensor nodes to request position estimate from the dynamic nodes.

Suprakash Datta proposed an on-demand TDMA slot assignment algorithm, RMAC (Randomized MAC), in which the sensor nodes ask the BS for slot assignments [DAT-04]. RMAC assumes that the sensor nodes are at one-hop distance from the BS. In every frame there are three phases: a contention phase during which the sensor nodes send requests to reserve communication slots, an acknowledgment phase in which the BS sends acknowledgments to the sensor nodes that succeed during the contention, and a communication phase in which each node uses the slot assigned by the BS to transmit its data. As a key contribution, RMAC finds the optimal number of minislots to be used during the contention period. The author points out that a large contention period reduces collision but increases per-packet latency and a small contention period increases collisions. Using a maximum likelihood estimate, RMAC estimates the number of packets based on the observation of the number of empty minislots, collided minislots, and successful minislots. It also predicts the number of packets in the next round using a simple linear predictor. Finally, it finds the number of minislots to be used in the next round by optimizing the expected delay of a packet.

Lee et al proposed a Flexible TDMA Protocol in [LEE-08], FlexiTP, which offers a synchronized and loose slot structure, where the sensor nodes in the network can build, modify, or extend their scheduled number of slots during execution, based on their local information. The sensor nodes stay in power-saving sleep mode except for their scheduled time slots. FlexiTP uses depth-first-search schedule which minimizes buffering. It allows the communication slots to be reused by the sensor nodes outside each other's interference range that makes it scalable.

There are several other MAC layer proposals which are not related to our work directly but an interested reader can refer to [BAC-10], which details a comprehensive survey on MAC layer protocols. Table 2.2 gives a summary of the proposed TDMA-based MAC layer protocols for WSNs that we have mentioned in this chapter.

Table 2.2: Comparison Table for TDMA-Based MAC schemes for WSNs

Protocols	Centralized Scheduling	Distributed Scheduling	Localization-Based Scheduling	Handling Node Mobility	Adapting to Traffic Changes	Multi-Channel
Pure TDMA <i>e.g. LEACH</i>	√	√				
TSMF	√					√
[ARI-02]	√					
PEDAMACS	√					
μMAC			√			
PACT		√			√	
FlexiMAC		√		√		
LMAC		√				
AI-MAC		√				
[INC-06]		√				√
SS-TDMA	√ (1 st time)	√				
[SHI-10]	√					
RandSched		√				
MCMAC			√	√		
DGRAM		√				
BMA	√				√	
EA-TDMA	√				√	
LASA	√				√	
BitMAC	√				√	
G-MAC	√				√	
SMACS		√			√	
TRAMA			√		√	
FLAMA			√		√	
EMACs			√		√	
PMAC			√		√	
RMAC	√				√	
FlexiTP		√			√	

Chapter 3

Achieving Reliability using Backup Cluster-Head

3.1 *Introduction*

In any application of the WSNs (Wireless Sensor Networks), the guaranteed coverage and monitoring of the whole sensor field is highly important. In cluster-based sensor networks, the CHs receive the data from the sensor nodes, aggregate them and then relay them to the BS (Base Station). In order to share the CH responsibility, cluster-based routing protocols rotate the CH responsibility among all the sensor nodes to avoid the single point of failure. However, a time comes when the energy of these sensor nodes reach a point where the sensor nodes may die being a CH. When these CHs die, they leave the whole cluster unmonitored. The important events and data, which are sensed by the sensor nodes, are not able to reach the sink or the BS. This may cause a substantial amount of data/event loss that may be crucial for some applications.

3.2 *Problem Definition*

In two tier cluster-based sensor networks, the sensor nodes are organized into local clusters, with one sensor node acting as the CH as shown in Figure 3.1. All the sensor nodes must transmit their data to the CH, while the CH must receive data from all the cluster members, perform signal processing functions on the data (e.g., data aggregation), and transmit data to the remote BS. Therefore, being a CH is much more energy-intensive

than being a non-CH. In the scenario where all sensor nodes are energy-limited, if the CHs were chosen a priori and fixed throughout the system lifetime, as in a static clustering algorithm, the CHs would quickly use up their limited energy. Once the CH runs out of energy, it is no longer operational. Thus, when a CH dies (e.g., uses up all its battery energy), all the nodes that belong to the cluster lose communication ability. Some existing protocols incorporate randomized rotation of the energy-intensive CH position such that it rotates among the sensor nodes in order to avoid draining the battery of any one sensor in the network. In this way, the energy load associated with being a CH is evenly distributed among all the sensor nodes.

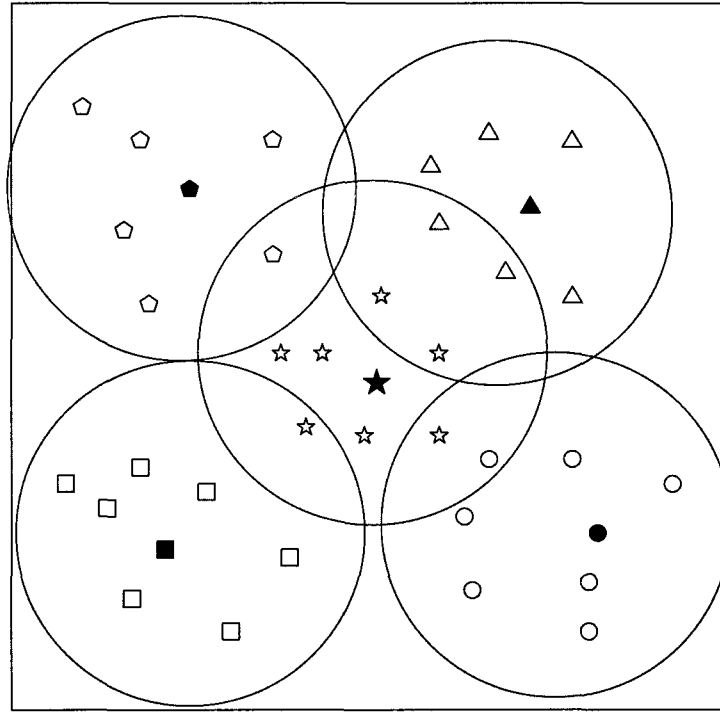


Figure 3.1: A regular cluster-based network topology

Almost in every cluster-based network protocol, where CH is rotated, the protocol operation is divided into rounds. As illustrated in Figure 3.2, each round begins with a cluster-formation/set-up phase when the clusters are organized, followed by a steady-state phase where several frames of data are transferred from the sensor nodes to the CH and onwards to the BS. All the sensor nodes are time-synchronized in order to start the set-up

phase at the same time. In order to minimize the set-up overhead, the steady-state phase is long compared to the set-up phase. Once the round is finished, the CH responsibility is rotated in the next round.

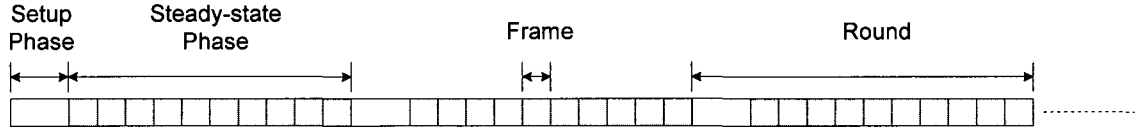


Figure 3.2: Time-line showing the operation. Clusters are formed during the set-up phase and data transfer occurs during the steady-state phase.

Normally the algorithms choose those sensor nodes as the CHs that have the highest energy in a cluster or in the whole network. However, when every sensor node has become a CH at least once in their lifetime then their residual energy is reduced and there will be a time when a sensor node with the most residual energy at then may also die being a CH. At this point during the steady-state phase, if the energy of a CH of any cluster depletes, the guaranteed coverage of that cluster falls in danger. The information gathered by that CH is also lost at that point. If the CH failure is undetected, then all the data sensed by the sensor nodes of that cluster and sent to the dead CH will be wasted. Even though rotation of the CH in the next round may help, in order to regain the coverage of the sensor field, but until the next CH selection, the whole cluster is unmonitored. If the steady-state phase is shortened to reduce the loss, it will increase the overhead of setup phase and still there will be losses due to the death of the CHs.

3.2.1 Example

In order to demonstrate this data loss effect, we chose LEACH-C protocol [HEI-00]. Other protocols or any LEACH-derived protocols will essentially give the same results because after the loss of the CHs they all perform the same way. Here we are illustrating the losses due to the death of the CHs only. Other channel losses and collision losses are not taken into consideration, as this is not the scope of this work. Figure 3.3 illustrates the Data Loss Ratio for LEACH-C protocol with 5 and 7-cluster networks. As it can be observed, until 340 seconds in 5-cluster network (and until 250 seconds in 7-cluster

network), there is no loss of data. After this time, the CHs start to die, resulting in the increase in *Data Loss Ratio (DLR)* and it continues until the whole network reaches its lifetime (*DLR* is defined in section 3.5). Overall 18-22% of the total data transmitted by the sensor nodes are lost.

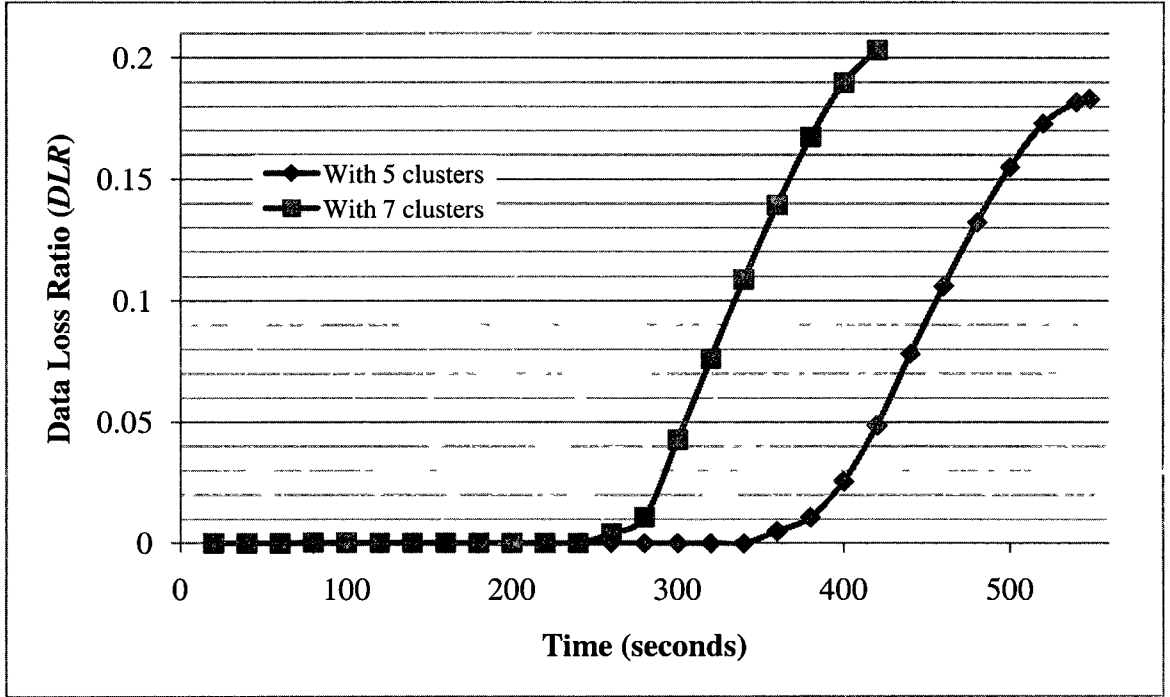


Figure 3.3: Data loss ratio in LEACH-C protocol

These data losses can be vital. Data transfer reliability in the WSNs is of huge importance for critical applications where the loss of single information about any event is crucial. To resolve this problem, we propose to have a BCH (Backup Cluster Head) for such CH, which cannot carry the CH responsibility throughout the round and may die before the end of the round.

3.3 Overview of the BCH Implementation

A BCH is selected in those rounds for those CHs where the residual energy level of the selected CHs is already at a threshold, and this idea addresses the issue and alleviates the damage that we discussed in the previous section. The selection of the BCH is not required when the WSN is initially deployed, as every sensor node has enough energy to

run the round as a CH. It has been assumed that the clustering protocols choose that sensor node as a CH, which has the highest energy in the cluster. The need of the BCH arises when every sensor node is expected to be exhausted during that particular round.

The flow charts given in Figures 3.4, 3.5 and 3.6, give the overview of the BCH implementation. During the setup phase, once the cluster is formed and the CH of the cluster is chosen, the energy of the CH is examined if it is enough to continue the whole round. If it can run the whole round alone, then it continues as normal. But if the energy is not enough then a BCH is selected for it, the next best sensor in that cluster. The information of the BCH is relayed to all the sensor nodes in the cluster. All the sensor nodes of the cluster then set their transmission power to reach both the CHs, current CH and BCH. This ensures that at the time of the CH switching, their transmission will still be reaching the BCH, and the CH switching will be seamless.

According to the residual energy of the CH, the watch dog timer is set for the BCH node, so it can start sending SOS message to CH once the timer fires. Until the timer fires, the BCH acts like a normal sensor node and sends its data at its scheduled time slot in every frame and then sleeps until the next transmission time slot arrives. Once the timer fires, the BCH then sends the SOS message to the CH, piggybacked with its data, then stays up, and listens for the SOS response. If no response is received then it sends another SOS message with the next data packet. It continues this way until it receives the SOS response from the CH and then assumes the CH responsibility.

The CH node once acknowledges that its energy is low and it is assigned a BCH then it checks for the SOS with all the packets coming from the BCH. If there is an SOS message then it checks for its own residual energy, if its energy is still above the threshold then it continues as a CH. But if the residual energy is less than the threshold, then it sends the SOS response to the BCH, transfers all the received data from the sensor nodes and becomes a normal sensor node. If the CH does not receive any SOS from the BCH due to any reason, like channel property degradation, packet collision, etc., and the residual energy of the CH goes below the threshold, then it still sends the SOS message to the BCH along with all the data that it gathered until that moment.

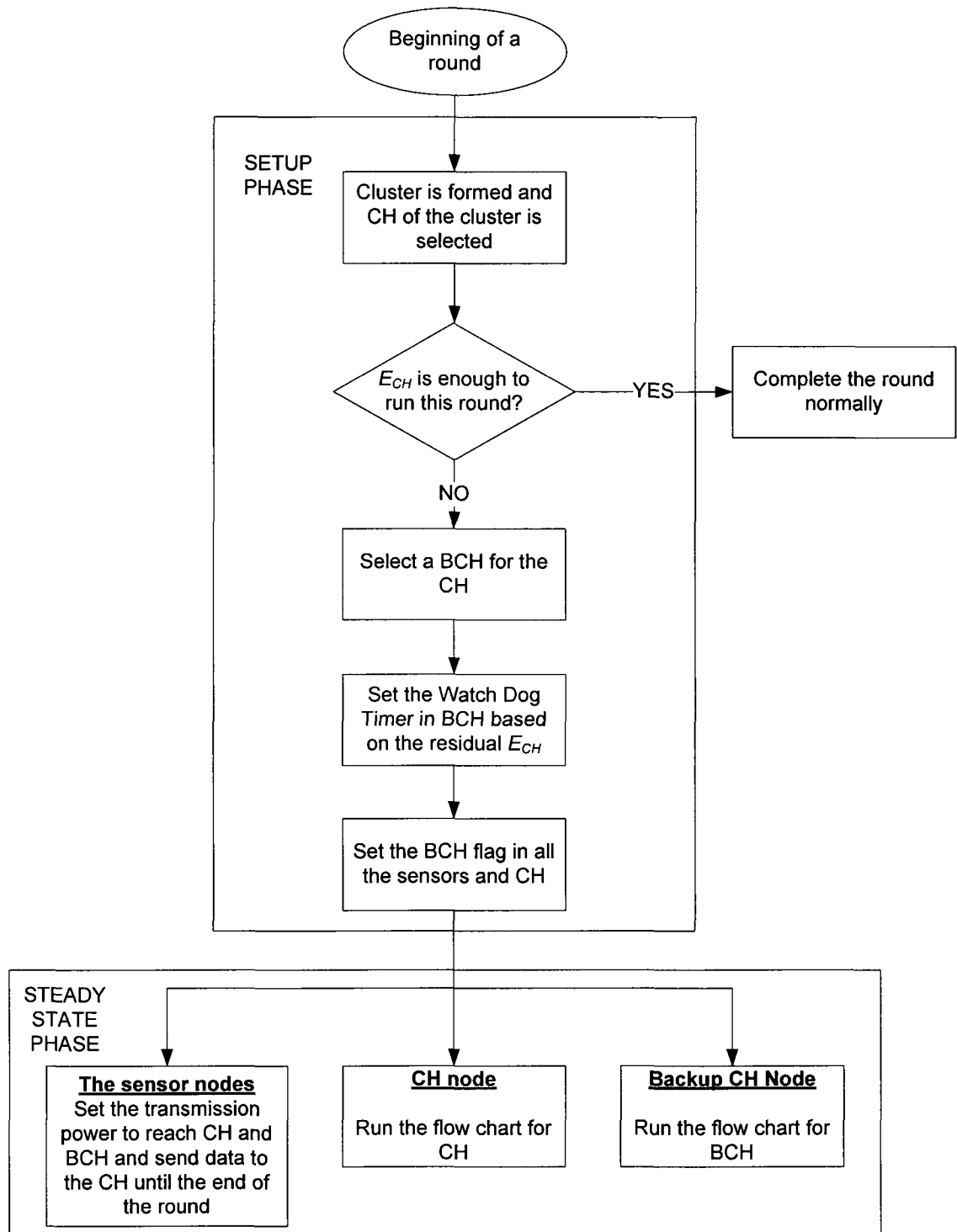


Figure 3.4: Flowchart of the system implementing BCH

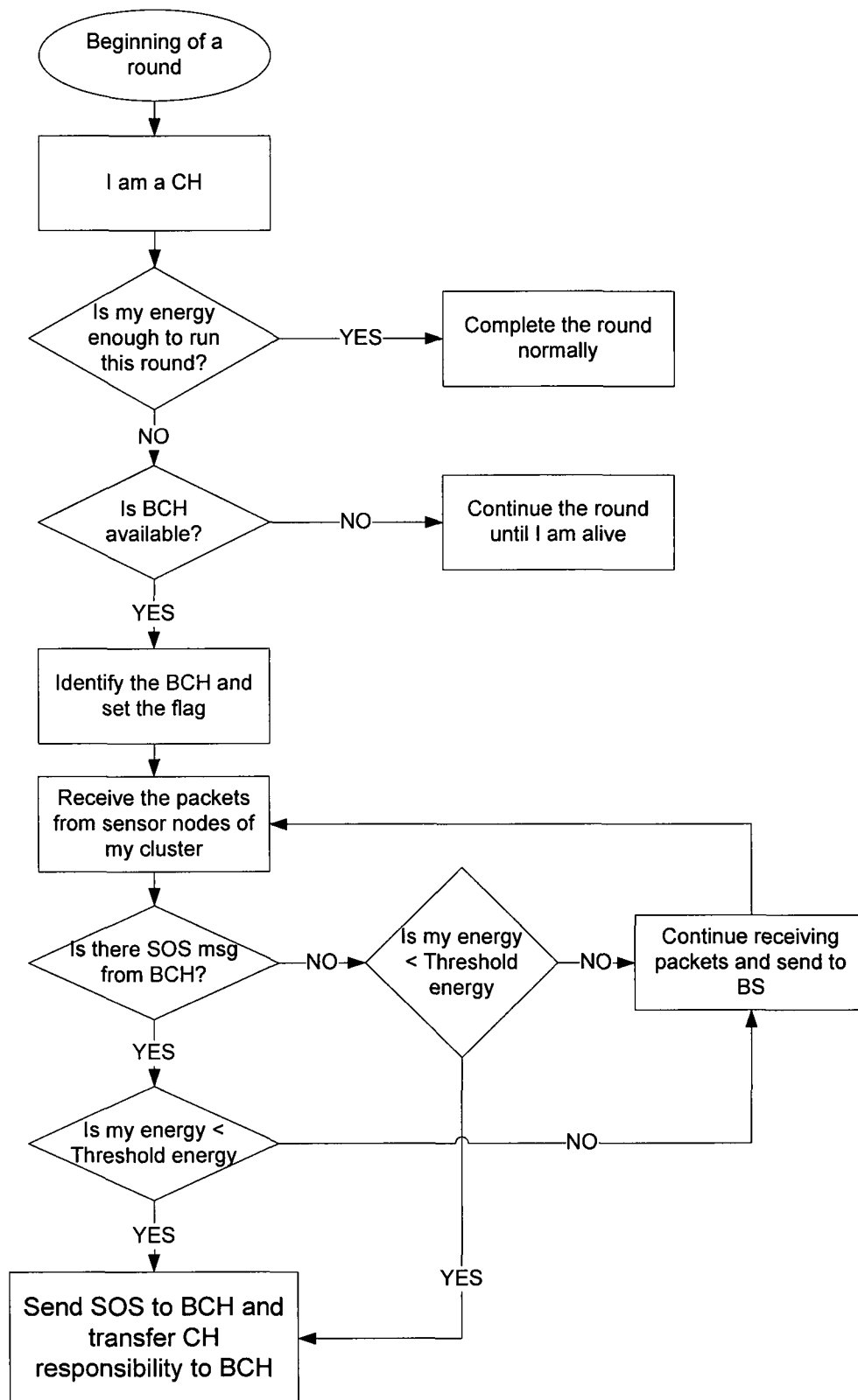


Figure 3.5: Flowchart of the operation of a CH

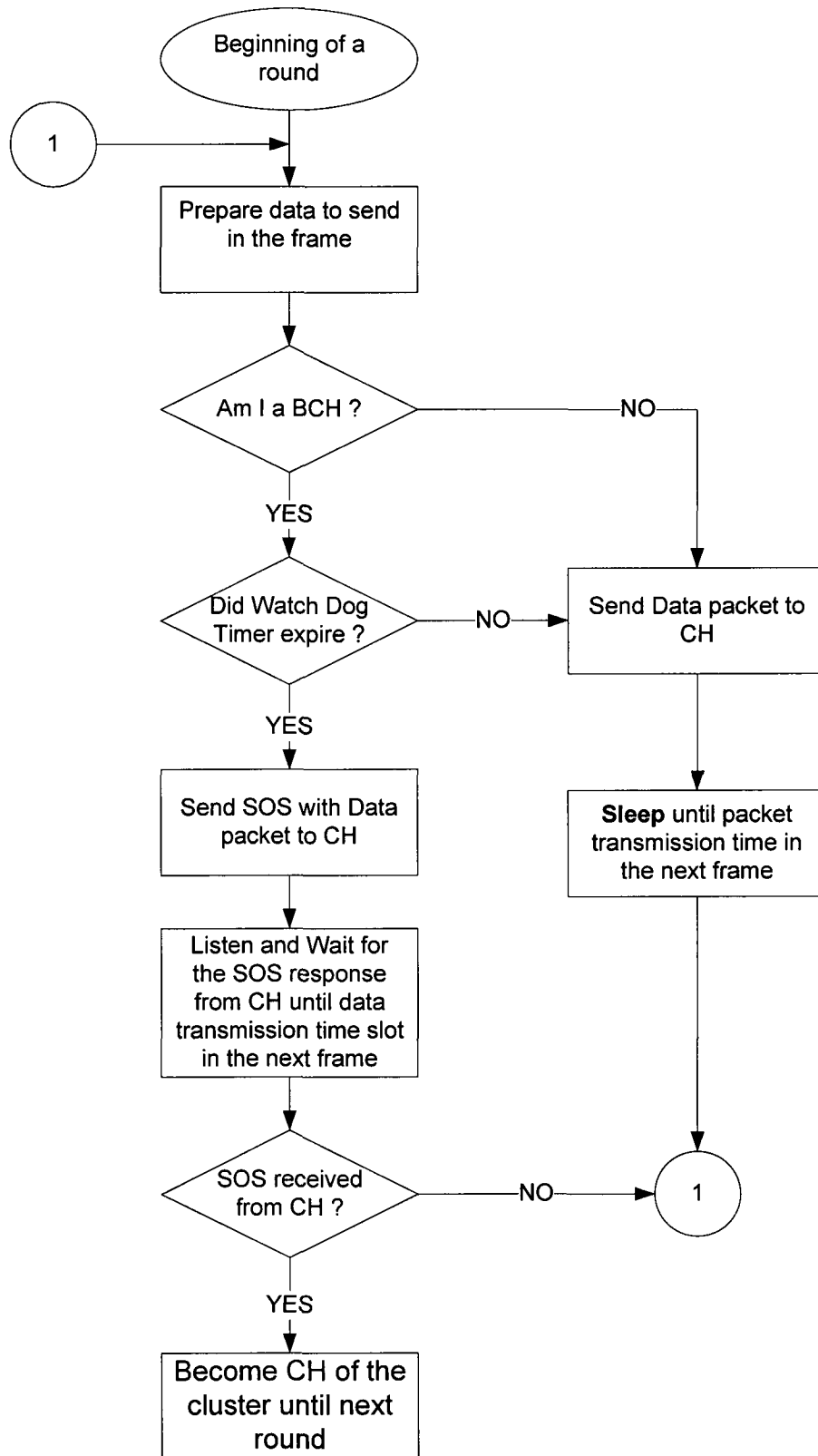


Figure 3.6: Flowchart of the operation of a BCH

By having all this methodology and applying the BCH approach, we can reduce the data loss due to the dying CHs. Of course, when the BCHs also die, then surely there will be loss, but will be far lesser than without a BCH. A Double Backup CH (DBCH) can also be assigned at the places where BCH is also expected to die sooner. Also, during the CH switching, the data sent by the sensor nodes to the CH will be lost, as in that period current CH would give up its task of receiving the data, and the BCH would not have assumed the CH responsibility.

3.4 Details of the BCH Framework

This section gives the details of the BCH implementation and explains all the steps which have been briefed in the previous section. As said earlier, the BCH is selected only in those rounds and assigned only to those CHs whose residual energy level is already at a threshold. The BCH method can be implemented on any cluster based protocol where the CH responsibility is rotated among the sensor nodes in a homogeneous WSN or in a heterogeneous environment where a few sensor nodes have more resources to be the CHs than other sensor nodes. To prove the viability of the BCH method, we chose LEACH protocol [HEI-00] to implement our proposal. Next is given the reasoning for why we chose LEACH protocol as a base protocol for our idea.

3.4.1 Why LEACH Protocol?

By the time, this proposal was published in the paper [HAS-07], quite a few two tier cluster based protocols were proposed. Our goal in this work is to show the viability of the BCH in any cluster oriented network. Chapter 2 details the existing two-tier networks. We had to choose a simple protocol where we can demonstrate the practicality of the BCH. That is why we chose LEACH protocol as a base protocol for our idea because of its simplicity and easy implementation. Other protocols like SEES [HOU-03], SAFE [KIM-03] and HEED [YOU-04] were also famous proposals but essentially, in every protocol whenever the CHs of the clusters start to die due to energy exhaustion, the performance curve will always be the same. The introduction of our BCH will give the same results in all the protocols. Our idea is not a protocol dependent; rather it can be implemented in any cluster-oriented network.

3.4.2 Clustering and the CH Selection

The clustering of the network and the CH selection for these clusters is employed the same way as has been proposed in the LEACH protocol. In fact, we chose a variant of the LEACH protocol, LEACH-C, proposed by the same author. In LEACH-C, the CH selection is done by the BS after receiving the energy status and the coordinates from all the sensor nodes. Having full data from all the sensor nodes, the selection process done by the BS is much better than the normal LEACH protocol and is proven by the author of LEACH [HEI-00]. Hence, it is more optimized and energy efficient, which should be a right comparison with clusters having BCH. The clustering process is also done by the BS, which creates an optimized cluster around the selected CH.

3.4.3 The BCH Selection

In the initial rounds when the WSN is deployed, a BCH is not needed, as most of the cluster-based protocols distribute the CH responsibility almost uniformly among the sensor nodes. The need of BCH arises when every sensor node in a cluster is expected to be exhausted during that particular round. The following explains the procedure of finding the eligibility of selecting a BCH for a CH.

During the setup phase, the sensor nodes with the highest energy in the given cluster regions are selected. Once the clusters and the CHs of the clusters are chosen, then the eligibility of having a BCH is checked. The BCH is then selected depending on the need.

Assume all the sensor nodes start off at the same initial energy, E_{ini} . Assume that the average energy consumption of a CH in a single round is $E_{CHcost/rnd}$. At the beginning of any round, during the setup phase, the residual energy of that node will be E_{res} . Assume that the energy of the would-be CH is E_{CHres} . Any sensor node after being selected as a CH will be eligible to have a BCH if the condition $\{E_{CHres} \leq E_{CHcost/rnd}\}$ is true. The calculation of $E_{CHcost/rnd}$ is explained later.

The BCH selection criterion is to choose a sensor node with the highest residual energy in the cluster of the concerned CH excluding the CH. The algorithm searches the sensor nodes with the highest energy in the whole cluster ($E_{MAXinCluster}$) and chooses that sensor as the BCH (as given in Algorithm 3.1). The CH is informed about the BCH, so it can

communicate with the BCH to send SOS message and relay the sensor information before it dies. All the sensor nodes of the cluster are also informed about the BCH, so when the CH dies, they may be able to send the sensor data to the BCH.

ALGORITHM 3.1. Selection of Backup and Double Backup Cluster-Head

```

maxER1 = 0                                # max. energy level for BCH 1
maxER2 = 0                                # max. energy level for BCH 2
backupCH1 = none
backupCH2 = none

for (I=0; I < allSensorNodesInTheCluster; I++) do
  if (I != myself) then
    sensor_I's_CurrentEnergy = sensorResidualEnergy;
    if (sensor_I's_CurrentEnergy > $maxER1) then
      if ((select doubleBackup?) == yes) then
        maxER2 = maxER1
        backupCH2 = backupCH1
      end
      maxER1 = sensor_I's_CurrentEnergy
      backupCH1 = I;
    elseif (((select doubleBackup?) == yes) & sensor_I's_CurrentEnergy >
                                                    $maxER2)
      maxER2 = sensor_I's_CurrentEnergy
      backupCH2 = I
    end
  end
end
end

```

3.4.4 The Second Backup CH Selection

By applying the BCH approach, we can reduce the data loss due to the dying CH nodes. But there may be a situation when the BCH may also die during the same round. That is, when the condition $\{(E_{CHres} + E_{MAXinCluster}) \leq E_{CHcost/rd}\}$ becomes true, then the selected BCH may also die and may leave the cluster unmonitored again. In this situation again, when the BCH also dies, surely there will be loss of data, but will be far lesser than without a BCH.

If this situation arises, we can have an option to select a second BCH for those clusters where even the primary BCH may also die. If the option of selecting two BCHs is enabled, then the sensor node with the second highest energy in the same cluster will be

chosen for that purpose (Algorithm 3.1).

3.4.5 The BCH Watchdog Timer

In most of the cluster-based protocols, it is suggested to put the sensor nodes' transceiver to sleep mode until the next data transmission, in order to save the energy consumption. If a sensor node is selected as a BCH, then it should stay awake and ready to take over the CH responsibility when needed. However, this will drain the BCH along with the current CH and will defeat the purpose of having a BCH. To avoid this situation, a watchdog timer is set in the BCH, during the setup phase of the round. So until this watchdog timer fires, the BCH should act like a normal sensor node and remain asleep. If we assume that the average energy consumed by a CH per second is $E_{CHcost/sec}$, then the time needed by the CH to deplete will be around $E_{CHres} / E_{CHcost/sec}$. So the BCH should be scheduled to wake up at such a time, that the taking over of the CH task could be done before the current CH expires. Therefore, the BCH wakeup time or Backup threshold time, $t_{BUthresh}$ should be

$$t_{BUthresh} = (E_{CHres} - E_e) / E_{CHcost/sec} \quad (3.1)$$

where E_e is the threshold energy level, below which a CH is susceptible to fail and it should be enough for transmitting SOS and aggregated data. The calculation of $E_{CHcost/sec}$ is given next. By implementing the BCH watchdog timer, we save the unnecessary wastage of the BCH energy, increase the lifetime of the BCH and hence increase the lifetime and reliability of the cluster.

3.4.6 Calculation of the CH Cost Per Round

For the calculation of $E_{CHcost/sec}$, we consider the average energy consumed on receiving the data from the w sensor nodes, $w \cdot E_{Rx}$, the energy spent on computing and aggregating the w data after each frame, $w \cdot E_{agg}$, and the energy consumed to transmit the data to the BS, $E_{CH \rightarrow BS}$. Hence the average energy consumed by the CH is

$$E_{CHcost/sec} = w \cdot E_{Rx} + w \cdot E_{agg} + E_{CH \rightarrow BS} \quad (3.2)$$

If the duration of a round is assumed rnd seconds, then $E_{CHcost/rnd}$ can be written as

$$E_{CHcost/rnd} = E_{CHcost/sec} * rnd \quad (3.3)$$

Equation (3.3) shows the energy consumption of a CH in a complete round. If a CH has enough energy in any round, then it does not need to have a BCH. But if that CH does not have enough energy to cover the whole round, then it has to be compensated by a BCH as described earlier.

3.4.7 Seamless CH Switching

The CH switching during a round should be in such a way that it should not hamper the cluster monitoring in order to inform all the sensor nodes about this transition. Here we have proposed a seamless switching of the CH responsibility that will accomplish these requirements. So once the BCH is selected in the setup phase then all the sensor nodes of the cluster are also informed that a BCH is available. These sensor nodes then set their transmission power to reach the two CHs, current CH and BCH. Then at the time of the CH switching, the sensor nodes do not have to be concerned about this process, and the CH switching will be seamless.

For example, as shown in the Figure 3.7, when the sensor node B sends its information to the CH, the BCH receives the data because it is in the range. However, when the sensor node A sends its information to the CH, the BCH will not be able to receive this information. Hence, the sensor node A need to set its transmission power in such a way that CH and BCH both will receive the data from the sensor node A. Hence to achieve seamless switching, the sensor node A will need to consume a little more energy than it would do without a BCH.

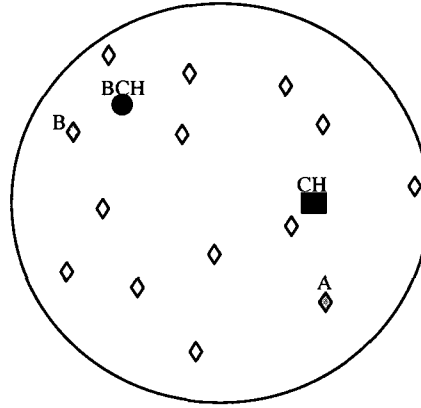


Figure 3.7: Setting the transmission range

3.4.8 Signalling for the CH Switching

The signalling for switching the CH task is quite straightforward. Every time when a BCH sends its data at its scheduled data transmission time slot, it checks for the expiry of watchdog timer $t_{BUthresh}$. If it is not expired, the BCH transmits the normal data in its time slot. But if the BCH finds that the $t_{BUthresh}$ timer is expired, the BCH sends its data packet at the scheduled time and sets the Data Type as SOS packet as illustrated in Figure 3.8.

<i>Data type</i>	<i>Source</i>	<i>Destination</i>	<i>Data size</i>	<i>Data</i>
SOS	src node (BCH ID)	dst node (CH ID)	length	data

Figure 3.8: SOS packet from BCH to CH

When the current CH receives the SOS message with the data packet, it checks its own residual energy. If its residual energy is below the threshold energy, E_e (i.e. $E_{res} < E_e$), such that it cannot continue further and its residual energy is not enough to survive another frame time, it then responds back to the BCH with the following packet, to take over and sends whatever data it has gathered until then. The SOS response packet is given in Figure 3.9.

However, if the residual energy of the CH is not below the threshold energy, E_e (i.e. $E_{res} > E_e$), and it deems that it can continue further and can survive another frame time, it will

not respond to the BCH. In this case, the BCH sends the SOS signal again with the next scheduled data packet. If the BCH data does not reach the CH somehow, then the current CH sends the above SOS signal before it dies, and transfers all the data that it gathered to the BCH.

<i>Data type</i>	<i>Source</i>	<i>Destination</i>	<i>Data size</i>	<i>Data</i>
SOS	src node (CH ID)	dst node (BCH ID)	length	all collected data

Figure 3.9: SOS response packet from CH to BCH

3.4.9 Loss During the CH Switching

It should be put in mind that during the CH switching, the data sent by the sensor nodes to the CH would be lost, as in that period the current CH would give up its task of receiving the data, and the BCH would not have assumed the CH responsibility. This data loss is inevitable; however, it is insignificant in comparison with the data loss occurring without a BCH.

Still there can be a way to avoid it. When the CH will give up its responsibility, it may inform all the sensor nodes to stop transmission for a specific duration of time or stop transmission until the BCH sends signal of its availability as a new CH. But this will not be anymore a seamless switching.

3.5 Performance Analysis

In order to evaluate the performance of the network with the BCH scheme we have used the LEACH-C protocol, and have compared the performance of pure LEACH-C to LEACH-C with BCH. As we are not addressing the cluster formation issue or cluster formation algorithm, we are just implementing the BCH scheme on an existing protocol. In fact, our BCH scheme can go along any cluster-based two-tier network.

As a performance metric, we compared the *Data Loss Ratio (DLR)* for network with and without the BCH scheme. The *DLR* is a ratio of the difference of total data sent by the sensor nodes and received at the BS to the total data sent by the sensor nodes, as given

below

$$DLR = \frac{TotalDataSent - TotalDataRcvd}{TotalDataSent} \quad (3.4)$$

For the sake of analysis, the CH has not used any data aggregation. Whatever data it received from the sensor nodes, are sent to the BS.

3.5.1 Network Model and Energy Model for the BCH

For our BCH method, we have used the same radio model for energy consumption by the nodes for transmitting and receiving data packets as used in LEACH [HEI-00]. It uses both the free space model and the multipath fading model, depending on the distance between the transmitter and the receiver. So for any distance between the transmitter and the receiver, which is less than a cross-over distance ($d_{crossover}$), the free space model is used (d^2 attenuation), otherwise the two-ray ground the propagation model (a multipath fading model) is used (d^4 attenuation) [HEI-00]. The cross-over distance is given by:

$$d_{crossover} = 4\pi h_r h_t \sqrt{L / \gamma} \quad (3.5)$$

where, $L \geq 1$ is the system loss factor not related to propagation, h_r is the height of the receiving antenna above the ground, h_t is the height of the transmitting antenna above the ground, and γ is the wavelength of the carrier signal.

If the distance d is less than $d_{crossover}$, the transmit power P_t is attenuated according to the free space equation to have the receive power P_r for distance d as follows:

$$P_r(d) = P_t G_t G_r \lambda^2 / (4\pi d)^2 L \quad (3.6)$$

where, G_t and G_r are the gains of the transmitting antenna and receiving antenna respectively. If the distance d between the transmitter and the receiver is greater than $d_{crossover}$, then the transmit power P_t is attenuated according to the two-ray ground propagation equation and the receive power will be:

$$P_r(d) = P_t G_t G_r h_t^2 h_r^2 / d^4 L \quad (3.7)$$

The energy consumption of the radio transmitter is set according to [HEI-00]. The free space path loss ϵ_{fs} for distances less than $d_{crossover} = 10\text{pJ/bit/m}^2$, while the multipath loss

ϵ_{mp} for distances more than $d_{crossover} = 0.0013\text{pJ/bit/m}^4$. The radio electronics cost E_{proc} has been set to 50nJ/bit. The data size has been 500 bytes/message plus a header of 25 bytes, $b = (500 \text{ bytes} + 25 \text{ bytes}) * 8 = 4200 \text{ bits}$. The equation for calculating the energy expended in transmitting a message to d meters is:

$$E_{Tx} = \begin{cases} b * E_{proc} + b * \epsilon_{fs} * d^2 : d < d_{crossover} \\ b * E_{proc} + b * \epsilon_{mp} * d^4 : d \geq d_{crossover} \end{cases} \quad (3.8)$$

and the amount of energy used when receiving a message is:

$$E_{Rx} = b * E_{elec} \quad (3.9)$$

Also, the parameters like radio speed, processing delay and radio propagation speed are all kept as in [HEI-00]. The energy model can benefit from improvements; however, this is outside the scope of this work.

3.5.2 Simulation Analysis

The simulation is performed using ns-2 simulator [ns-2]. We kept the same simulation environment as in [HEI-00]. The network size is 100 x 100 meters with 100 nodes randomly distributed and the BS located at 75 meters outside the area where the sensor nodes were deployed. The BS reschedules the CHs every 20th second. Each node sends a message to its CH during a given time slot. All the sensor nodes start with 2 Joules of energy and the simulation continues until all the sensor nodes in the network have consumed all of their energy. The total simulation time also represents the total lifetime of the network. In order to make comparisons possible, we have used the same channel propagation model, radio energy model and beamforming energy model as in LEACH [HEI-00]. Table 3.1 shows the characteristics of the network.

Table 3.1: Characteristics of the Network for BCH Simulation

Network size	100 x 100 m
BS location, (x, y position)	50, 175
Total number of nodes	100
Processing delay	50us
Data transfer rate	1 Mbps
Data size	500 bytes
Antenna gain, Gt & Gr	1

We ran the simulation with 5-cluster network and 7-cluster network to see the effect of having BCH. The *DLR* is calculated for the data sent globally in the network and received at the BS for the whole network. As illustrated in Figure 3.10, when the packets start to be lost, the *DLR* for the BCH-based LEACH-C is almost $1/3^{\text{rd}}$ of pure LEACH-C, while at the end of network lifetime; overall data loss is still a little more than half of pure LEACH-C. In Figure 3.11, where 7 clusters were setup, the overall data loss is even less than half of pure LEACH-C, as the BCH is more effective for higher number of clusters. Implementing the BCH scheme did decrease the network lifetime but by only less than 2%, as the sensor nodes here are used as backup CHs, which in case of pure LEACH-C have been just sensing data. We also simulated Double Backup CH as depicted in Figure 3.10 and Figure 3.11. It has not reduced the data loss that much, as most of the sensor nodes have been already exhausted by the end, which have been also kept on dying. As described in Appendix B, the tests have been repeated over at least 8 times, at the end of which the mean, upper bound and lower bound have been computed for the confidence interval of 95%. Since the confidence intervals are very small, they are visible for a few results in the curves, however, examples of the computations can be found in Appendix B.

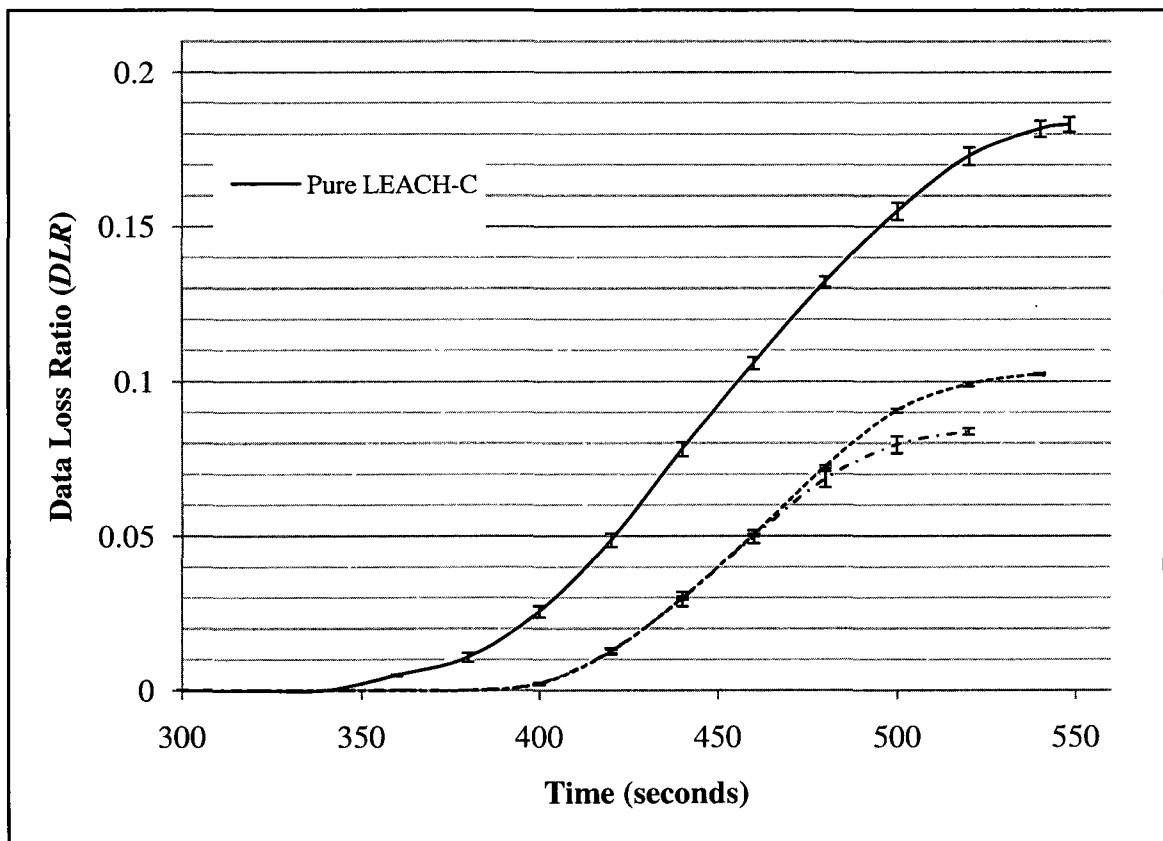


Figure 3.10: *Data Loss Ratio* in a round with and without the BCH with 5 clusters in the network.

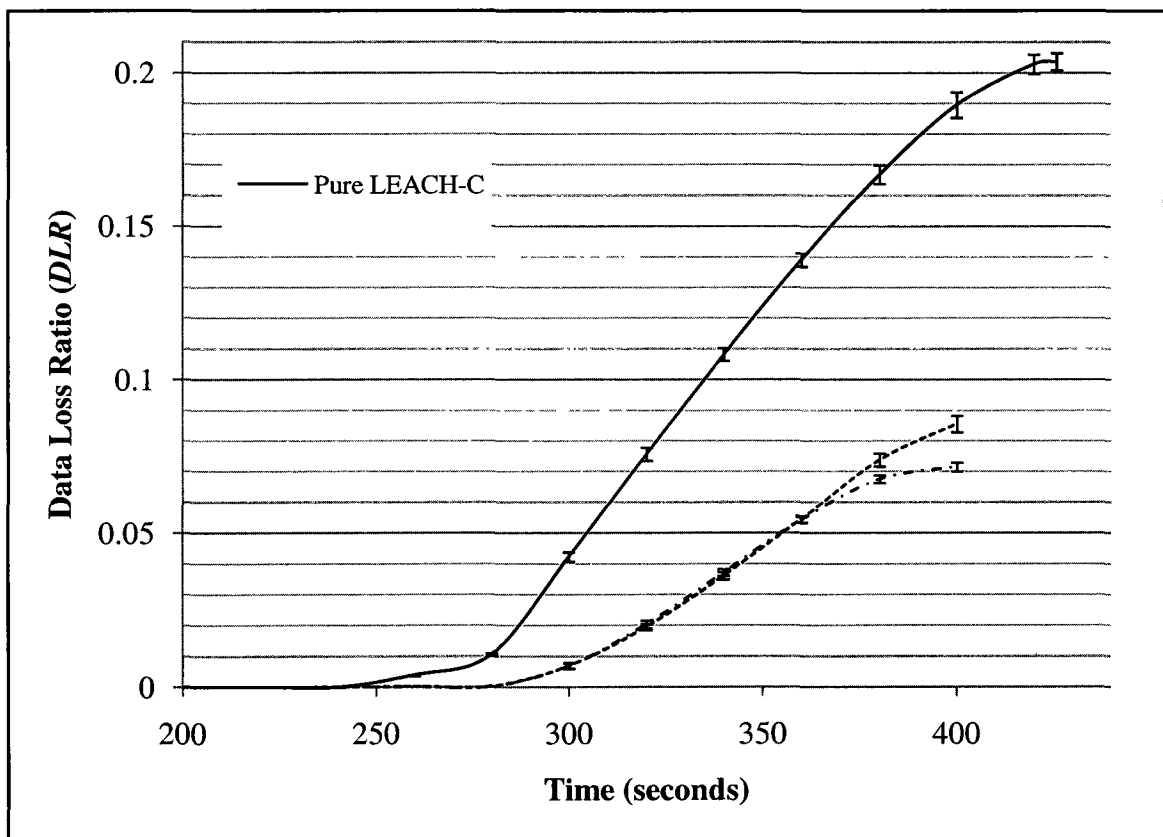


Figure 3.11: *Data Loss Ratio* in a round with and without the BCH with 7 clusters in the network.

3.6 *Summary*

We have presented the BCH framework, which provides data transfer reliability in terms of data loss reduction and increases the cluster monitoring duration in a round. We achieve this by selecting a BCH for the CHs which are not able to complete the round as a CH and may die, rendering the whole cluster unmonitored until the end of the round. The BCH in the corresponding cluster is selected as the future leader of that cluster, which assumes its responsibility when the original CH dissipates all its energy.

A watchdog timer is established in the BCH at the beginning of the round, which saves the BCH energy by allowing it to sleep and act as a normal sensor node until the timer expires. When the timer expires, the BCH starts sending the SOS message to show its availability to the current CH. If the CH is ready to initiate the CH transition, it responds the SOS message to the BCH; otherwise continue to be the CH until the next SOS arrives.

The framework that is given in this chapter provides a seamless CH transition from the original CH to the BCH, and the sensor nodes do not even know of this transition. This is achieved by setting the transmission power of the sensor nodes in such a way that when they send their data packets, they reach both the CHs, the original CH and the BCH.

Chapter 4

Analytical Model of the Backup Cluster-Head

4.1 *Introduction*

In this chapter, we present an analytical model of the cluster reliability in cluster-based WSNs using BCH, based on Markov chain model [HAS-10c]. We use non-homogeneous Markov process, along with Forward Chapman-Kolmogorov equations to illustrate the cluster-monitoring period in a finite three state space model. We test the accuracy of the model by applying the probabilities of failure of the CH and the BCH, for a fixed number of sensor nodes in a cluster. The results show that the presented model is able to match the behaviour of the cluster state transition accurately and validates the simulation results and analysis given in the previous chapter. The implementation of the BCH delays the cluster failure and increases the cluster reliability. The presented reliability model can be applied to any three-state fault-tolerance system having varying transition probabilities and a given initial state probability vector.

4.2 *Markov Chain Model*

The theory of the Markov chains is the basis of many of the most powerful analytical techniques for evaluating computer system performance (and many other systems) [GRI-94], [ISA-95]. The Markov analysis provides a means of analyzing the reliability and availability of systems whose components exhibit strong dependencies. Systems are

described by state transition diagrams and may be used to model repairable systems with constant failure and repair rates. The Markov states characterize all possible situations that the system can exist in. The system can only ever be in one state at a time and a single state must be set up as the initial starting state. Transitions from one state to another in the Markov diagram are represented by the transition rates at which they move. For example, the transition rate from a failed state to a working state is represented by the repair rate whereas the transition from a working state to a failed state is represented by the failure rate.

The Markov model is investigated to determine such measures as the probability of being in a given state at a given point in time, the amount of time a system is anticipated to spend in a given state as well as the expected number of transitions between states, for instance representing the number of failures and repairs.

Graphically, a Markov model is usually represented in the shape of nodes and arrows, where the nodes symbolize the states that the system can be in, and the arrows symbolize the transitions between the states. The numerical parameters of the model, θ_{ij} , where i and j are used to show the source and destination of the transitions, is referred to the transition rate, going from state i to state j .

4.3 ***Mathematical Preliminaries***

4.3.1 **Non-Homogeneous Markov Chain**

A Markov chain is a discrete-state random process in which the succession of the state of the process at time l (continuous-time chain) or t (discrete-time chain) depends only on the present state X_l or X_t respectively, and is independent of how the chain has reached its present state or how long it has been in that state [TRI-02]. To illustrate, assume a random sequence $\{X_t; t = 0, 1, 2 \dots\}$, for every time t and all possible states of the X_t

$$P[X_{t+1} = j | X_0 = a, X_1 = b, \dots, X_t = i] = P[X_{t+1} = j | X_t = i] \quad (4.1)$$

This is called the Markov property and it means that the probability of any future state, given the entire past and present states, is totally independent of the past events and depends only on the current state of the process. Similarly, the conditional probabilities

like $P[X_{t+1} = j | X_t = i]$ are called transition probabilities and are denoted by $\theta_{ij}(t)$. In a Non-homogeneous Markov chain the transition probabilities of going from state i to state j , $\theta_{ij}(t)$, vary with time t and never stay constant.

4.3.2 Chapman-Kolmogorov Equations

We can put a simple recursion equation for the state probabilities of a general Markov chain. Suppose that the probability that X_{t+1} takes on state j is $P_j(t+1)$. Now at time t the system may be in any state i with probability $P_i(t)$, $i = 1, 2, \dots, k$. For every state i , there is a transition probability $\theta_{ij}(t)$, that the system will make the transition from state i to state j . If we know the state probability vector at time t , we can compute the j_{th} component of the vector at time $t + 1$, as given below

$$P_j(t+1) = P_1(t)\theta_{1j} + P_2(t)\theta_{2j} + \dots + P_k(t)\theta_{kj} = \sum_{i=1}^k P_i(t) \cdot \theta_{ij}(t) \quad (4.2)$$

The set of k such equations can be summarized in a matrix and vector representation

$$\mathbf{Pr}(t+1) = \mathbf{Pr}(t) \cdot \Delta(t) \quad (4.3)$$

where $\mathbf{Pr}(t)$ is a k -dimensional row vector with elements $P_i(t)$, $i = 1, 2, \dots, k$, and Δ is a $k \times k$ matrix with elements $\theta_{ij}(t)$ and is called Markov chain transition probability matrix at time t . These are called forward Chapman-Kolmogorov equations [BER-92]. If the process is non-homogeneous or nonstationary, then from Equation (4.3) we have

$$\mathbf{Pr}(t) = \mathbf{Pr}(0) \cdot \Delta(0) \Delta(1) \Delta(2) \Delta(3) \dots \Delta(t-1) \quad (4.4)$$

And if the process is homogeneous or stationary and independent of t , then

$$\mathbf{Pr}(t) = \mathbf{Pr}(0) \cdot \Delta^t \quad (4.5)$$

If we know the transition probability matrix Δ and the initial state probability vector $\mathbf{Pr}(0)$, then from Equation (4.4) we can have the state probabilities of a Markovian chain, completely determined for all $t > 0$.

It is clear from the definition of conditional probabilities that the elements of the transition matrix Δ must satisfy the following properties,

$$\theta_{ij}(t) \geq 0 \quad \text{for all } i, j \quad \text{and } t=0,1,2,\dots \quad (4.6)$$

and

$$\sum_{i=1}^K \theta_{ij}(t) = 1 \quad \text{for all } i \quad \text{and } t=0,1,2,\dots \quad (4.7)$$

Matrices satisfying these above two conditions are called stochastic matrices, and any stochastic matrix may serve as a transition probability matrix.

4.3.3 Absorbing Markov Process

An *absorbing Markov process* is a Markov process that will eventually stop at a particular state and is impossible to leave that state. The states at which the process might stop are called *absorbing states* [TRI-02]. If state i is an absorbing state, then the transition probability from state i to state j (θ_{ij}) will be zero for all $j \neq i$ and will be 1 for $j = i$.

4.4 Problem Formulation

With the help of the BCH methodology, we want to maximize the cluster monitoring duration in every round. In BCH protocol, along with reducing the data loss, a key feature is the smooth CH responsibility transfer between the CH and the BCH. It is designed to let these nodes communicate with each other by using the SOS messages, which helps to take the switching decision at the right time. This decision takes place based on the battery power level of the CH node, and they are executed by setting data type in their SOS messages. However, these SOS messages can be corrupted, for example due to packet collisions or channel noise, or they might not be sent at the right time. All these assumptions and the cluster status, lead to a simple three state non-homogeneous Markov chain model, describing the possible states for that cluster, as shown in Figure 4.1

Now, we formulate the problem and then derive the approximate mathematical model that can represent our BCH scheme. This model is based on Markov chain model as given in Figure 4.1. The following are the details of the states of this Markov chain:

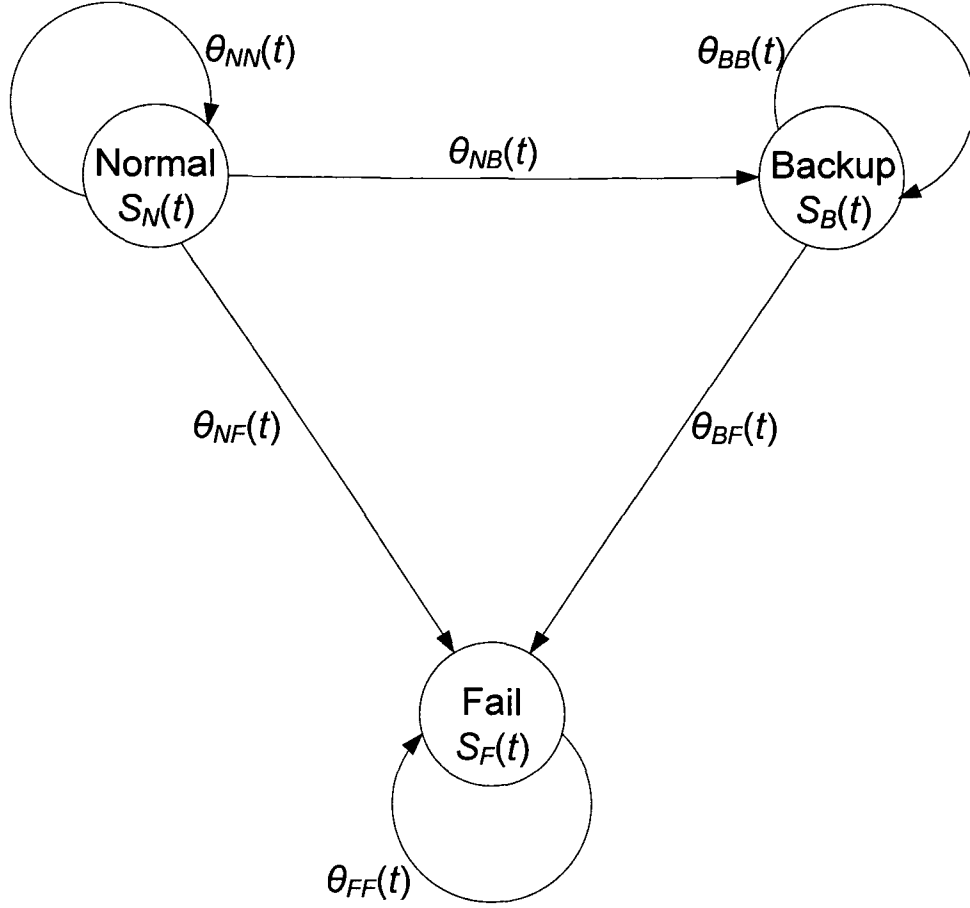


Figure 4.1: A state transition diagram showing the three states and the probabilities of going from one state to another

Normal State: Every round begins with this state. The CH is elected or selected and a BCH is selected based on the need. Data transmission to the CH occurs in this state.

Backup State: This is the state when the CH responsibility has been successfully switched from the current CH to the BCH, after a successful communication with the help of SOS messages.

Fail state: This state means that the cluster is in nonmonitoring state. There are two ways for a cluster to get into this state. One is from the *Normal* state, when the protocol fails to do the CH switching, i.e. when the SOS messages that are sent by the CH to the BCH or vice versa are corrupted. Therefore, the BCH misses its CH's SOS message and the CH dies rendering the cluster unmonitored until the next round

begins. The second scenario is from the *Backup* state, when the BCH itself runs out of the energy and dies. Hence, in this situation again the cluster is in a state of no CH until next round.

Let us consider that S_N , S_B and S_F are the state probabilities of being in *Normal*, *Backup*, and *Fail* states, respectively. We assume that the *Normal* state is considered as an initial state ($t = 0$), so the initial state matrix is stated as $[1 \ 0 \ 0]$. Generally, the analysis of a Markov model involves the computation of the state probability to have the system in a given state as a function of time. For instance, assuming that at $t = 0$ the system is in *Normal* state, computations are executed to determine the probabilities that the system will be in *Normal*, *Backup* and *Fail* states at any given time t . At each point in time, the sum of probabilities of the states must add up to 1. If the probability of the system being in one state decreases by a certain amount, then that same amount must be distributed over the other states in the system. Therefore, Fig. 4.1 can be represented by the following equation based on Equation (4.3):

$$\begin{bmatrix} S_N & S_B & S_F \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_{NN} & \theta_{NB} & \theta_{NF} \\ \theta_{BN} & \theta_{BB} & \theta_{BF} \\ \theta_{FN} & \theta_{FB} & \theta_{FF} \end{bmatrix} \quad (4.8)$$

So we can get the state probability of each state based on the transition probabilities by using the Markov chain model given above. However, there are a few factors that might have some impact on these states, so we will first discuss them before calculating the transition probabilities.

4.4.1 Impact of the BCH Watchdog Timer

The BCH node sends the SOS message piggybacked with its data packet. When the BCH sends the SOS message to the CH to indicate that it is available for the CH responsibility transfer, then the BCH has to stay awake in order to receive the SOS request from the CH. This staying awake consumes extra energy of the BCH, and reduces its lifetime. To keep it small, the BCH watchdog timer or Backup threshold timer ($t_{BUthresh}$) is set. After the threshold timer expires, the BCH sends the SOS message and remains awake to receive the SOS response from the CH. Once it receives the SOS message from the

CH, the BCH takes over the responsibility and the cluster then enters into the *Backup* state successfully. If this timer expires late, then the CH may die before the transfer of responsibility and enter into the *Fail* state. If the timer expires too early, then the BCH will consume more energy by staying awake unnecessarily. Therefore, this timer has to be calculated carefully and should be optimized between both situations.

The calculation of $t_{BUthresh}$ depends on the average energy consumed by a CH per second, $E_{CHcost/sec}$, as given below:

$$t_{BUthresh} = (E_{CHres} - E_{\epsilon}) / E_{CHcost/sec} \quad (4.9)$$

where E_{CHres} is the residual energy of the CH at the start of the round and E_{ϵ} is the threshold energy level, below which a CH is susceptible to fail.

The CH node consumes energy $E_{Rx/sec}$ in receiving the data from w sensor nodes in its cluster, $E_{agg/sec}$ in aggregating the received data from the same number of sensor nodes and then consumes $E_{CH \rightarrow BS}$ in transmitting the aggregated data to the BS. Hence, the energy consumed by a CH node in every second can be calculated as:

$$E_{CHcost/sec} = w \cdot E_{Rx/sec} + w \cdot E_{agg/sec} + E_{CH \rightarrow BS} \quad (4.10)$$

The probability that the energy of the CH is going towards the threshold energy level, E_{ϵ} , at any time t can be found by

$$P_{CH \rightarrow L}(t) = 1 - \frac{E_{CHres} - E_{CH \cos t / sec} * t - E_{\epsilon}}{E_{CHres} - E_{\epsilon}} \quad (4.11)$$

The above relation is a linear equation and this is due to the fact that the above probability depends on the energy consumption of the CH over time ' t ', which is a constant value.

Similarly, when the cluster is moved to the *Backup* state, then the probability of the BCH energy depleting to zero level, $P_{BCH \rightarrow 0}(t)$, can be calculated by using the residual energy of the BCH at the time of the CH switching, E_{BCHres} .

$$P_{BCH \rightarrow 0}(t) = 1 - \frac{E_{BCHres} - E_{CH \cos t / sec} * t}{E_{BCHres}} \quad (4.12)$$

4.4.2 Impact of the Data Traffic

We assumed those sensor network applications where the data availability is deterministic and the sensor nodes in the cluster are assumed to have data in every frame. Therefore, the data traffic intensity may not vary during the course of a single round. Applying the BCH methodology to other sensor network applications, where the data traffic is varying and non-deterministic, then it may affect the CH life and may die early. So while setting the ' $t_{BUthresh}$ ' parameter we will have to consider this factor as well. In our model for the deterministic data traffic applications, the Markov model will be unaffected.

4.4.3 Impact of the Wireless Channel Characteristics

The wireless channel is considered as a lossy and unreliable link because its quality changes with time and experiences higher error rates than wired communications. Hence, the wireless network is not able to achieve the wired network performance. Other factors like attenuation, interference, and multipath fading affect the wireless channel all the time. These channel characteristics of the WSN offer a great challenge in its design that has to counter and manage all these issues. For the Markov model we discussed earlier, the cluster enters the Fail state when the SOS message is corrupted due to the channel errors. Study of the channel characteristics is out of the scope of this work, but the interested reader is referred to [KON-03], [BAI-03] to know more about the wireless channel error models.

4.5 Model Analysis

The transition probability from the *Normal* state to the *Backup* state, $\theta_{NB}(t)$, depends entirely on the probability of the CH energy going below the threshold level, i.e. $P_{CH \rightarrow L}(t)$, and there is no other factor that affects this transition. So, θ_{NB} is given by

$$\theta_{NB}(t) = P_{CH \rightarrow L}(t) \quad (4.13)$$

The transition probability from the *Normal* state to the *Fail* state, $\theta_{NF}(t)$, depends on the wireless channel characteristics and the network MAC protocol. The cluster enters the *Fail* state when the CH-transfer is unsuccessful due to either collision, fading, interference, or hidden terminal phenomenon. This is expressed by the wireless channel

probability of error, P_{error} . Therefore

$$\theta_{NF}(t) = P_{error} \quad (4.14)$$

So the probability that the energy level of the CH does not drop below the threshold, E_e , can be represented by $(1 - P_{CH \rightarrow L}(t))$, and the probability that there is no error in the wireless channel can be represented by $(1 - P_{error})$.

Similarly, the transition probability from the *Backup* state to the *Fail* state, $\theta_{BF}(t)$, depends on the probability of energy of the BCH depleting to zero level, given by $P_{BCH \rightarrow 0}(t)$. The probability that the cluster remains in the *Backup* state, $\theta_{BB}(t)$, depends on the probability that the energy level of the BCH does not deplete to zero level, i.e. $(1 - P_{BCH \rightarrow 0}(t))$. Hence, the two probabilities can be written as

$$\theta_{BF}(t) = P_{BCH \rightarrow 0}(t) \quad (4.15)$$

$$\theta_{BB}(t) = 1 - P_{BCH \rightarrow 0}(t)$$

Once the cluster goes in the *Fail* state then it stays there until the round finishes, with $\theta_{FF}(t) = 1$. The main target of this work is to avoid the cluster going in to the *Fail* state.

Now we can calculate the state probabilities of the *Normal*, *Backup* and *Fail* states, denoted as $S_N(t)$, $S_B(t)$ and $S_F(t)$, respectively. When the cluster is formed and the sensor nodes start communication, the cluster starts in the *Normal* state, i.e. $S_N(0) = 1$. However, as the communication continues and the CH starts to lose the energy, $S_N(t)$ along with $\theta_{NN}(t)$ also decreases. From the Markov properties

$$\theta_{NN}(t) + \theta_{NF}(t) + \theta_{NB}(t) = 1 \quad (4.16)$$

or can be rewritten as

$$\begin{aligned} \theta_{NN}(t) &= 1 - \theta_{NF}(t) - \theta_{NB}(t) \\ &= 1 - P_{error} - P_{CH \rightarrow L}(t) \end{aligned} \quad (4.17)$$

When the round is started at $(t = 0)$, the *Normal* state is considered as an initial state of the cluster, so the initial state matrix $\mathbf{Pr}(0)$ is stated as $[S_N(0) \ S_B(0) \ S_F(0)] = [1 \ 0 \ 0]$. Since the Markov model we considered, is a non-homogeneous Markov process, therefore the transition matrix changes with time t . From Figure 4.1, the matrix of transition

probabilities $\Delta(t)$ can be represented as

$$\Delta(t) = \begin{bmatrix} \theta_{NN}(t) & \theta_{NB}(t) & \theta_{NF}(t) \\ 0 & \theta_{BB}(t) & \theta_{BF}(t) \\ 0 & 0 & \theta_{FF}(t) \end{bmatrix} = \begin{bmatrix} \theta_{NN}(t) & \theta_{NB}(t) & \theta_{NF}(t) \\ 0 & \theta_{BB}(t) & \theta_{BF}(t) \\ 0 & 0 & 1 \end{bmatrix} \quad (4.18)$$

The transition matrix exhibits that it is an Absorbing Markov chain where the *Fail* state is an absorbing state because once the cluster is in this state, the cluster remains in this state until the end of the round. With the given initial state probability vector $\mathbf{Pr}(0)$ and transition probability matrix $\Delta(t)$, we can compute the evolution of the state probability vector for as many transitions as we want by repeated application of the Chapman-Kolmogorov equations, as below:

$$\begin{aligned} \mathbf{Pr}(t+1) &= [S_N(t+1) \quad S_B(t+1) \quad S_F(t+1)] \\ &= \mathbf{Pr}(t) \cdot \Delta(t) \\ &= [S_N(t) \quad S_B(t) \quad S_F(t)] \begin{bmatrix} \theta_{NN}(t) & \theta_{NB}(t) & \theta_{NF}(t) \\ 0 & \theta_{BB}(t) & \theta_{BF}(t) \\ 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (4.19)$$

Therefore, we can get the probability of each state, based on the transition probabilities by using the Chapman-Kolmogorov equations on the non-homogeneous Markov chain model given above. As mentioned earlier, when the probability of the CH energy goes below the threshold level, i.e. $P_{CH \rightarrow L}(t)$, the cluster transitions from *Normal* state to *Backup* state. Say the transition occurs at $t = t_{NB}$, and the duration before this transition is equal to T_N , as in the timeline given in Figure 4.2.

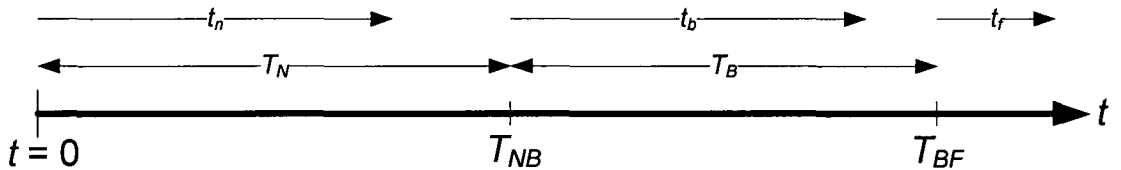


Figure 4.2: Timeline for cluster state transitions

Before the transition from *Normal* state to *Backup* state, $\theta_{BB}(t)$ will be equal to one and $\theta_{BF}(t)$ will be 0. From Equation (4.19), the state probability vector $\mathbf{Pr}(1)$ at $t = 1$ can be given as:

$$\begin{aligned}\mathbf{Pr}(1) &= \mathbf{Pr}(0) \cdot \Delta(0) = [S_N(0) \quad S_B(0) \quad S_F(0)] \cdot \begin{bmatrix} \theta_{NN}(0) & \theta_{NB}(0) & \theta_{NF}(0) \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= [S_N(0) \cdot \theta_{NN}(0) \quad S_N(0) \cdot \theta_{NB}(0) + S_B(0) \quad S_N(0) \cdot \theta_{NF}(0) + S_F(0)]\end{aligned}\quad (4.20)$$

Similarly $\mathbf{Pr}(2)$ and $\mathbf{Pr}(3)$ at $t = 2$ and $t = 3$ respectively, can be given as:

$$\begin{aligned}\mathbf{Pr}(2) &= \mathbf{Pr}(1) \cdot \Delta(1) \\ &= [S_N(0) \cdot \theta_{NN}(0) \quad S_N(0) \cdot \theta_{NB}(0) + S_B(0) \quad S_N(0) \cdot \theta_{NF}(0) + S_F(0)] \\ &\quad \cdot \begin{bmatrix} \theta_{NN}(1) & \theta_{NB}(1) & \theta_{NF}(1) \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NN}(1) & S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NB}(1) & S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NF}(1) \\ S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NB}(0) & + S_N(0) \cdot \theta_{NB}(0) & + S_N(0) \cdot \theta_{NF}(0) \\ + S_B(0) & & + S_F(0) \end{bmatrix}\end{aligned}\quad (4.21)$$

$$\begin{aligned}\mathbf{Pr}(3) &= \mathbf{Pr}(2) \cdot \Delta(2) \\ &= \begin{bmatrix} S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NN}(1) & S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NB}(1) & S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NF}(1) \\ + S_N(0) \cdot \theta_{NB}(0) & & + S_N(0) \cdot \theta_{NF}(0) \\ + S_B(0) & & + S_F(0) \end{bmatrix} \\ &\quad \cdot \begin{bmatrix} \theta_{NN}(2) & \theta_{NB}(2) & \theta_{NF}(2) \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\end{aligned}\quad (4.22)$$

$$= \begin{bmatrix} S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NN}(1) \cdot \theta_{NB}(2) & S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NN}(1) \cdot \theta_{NF}(2) \\ S_N(0) \cdot \theta_{NN}(0) & + S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NB}(1) & + S_N(0) \cdot \theta_{NN}(0) \cdot \theta_{NF}(1) \\ \cdot \theta_{NN}(1) \cdot \theta_{NN}(2) & + S_N(0) \cdot \theta_{NB}(0) & + S_N(0) \cdot \theta_{NF}(0) \\ + S_B(0) & & + S_F(0) \end{bmatrix}$$

Hence, at any time $t = t_n$ during the period of T_N , we can find a general state probability vector $\mathbf{Pr}(t_n)$ as follows:

$$\mathbf{Pr}(t_n) = \begin{bmatrix} S_N(0) \prod_{i=0}^{t_n-1} \theta_{NN}(i) \\ S_B(0) + S_N(0) \left\{ \sum_{j=0}^{t_n-1} \left[\theta_{NB}(j) \cdot \prod_{i=1}^j \theta_{NN}(i-1) \right] \right\} \\ S_F(0) + S_N(0) \left\{ \sum_{j=0}^{t_n-1} \left[\theta_{NF}(j) \cdot \prod_{i=1}^j \theta_{NN}(i-1) \right] \right\} \end{bmatrix}^T \quad (4.23)$$

Since the initial state vector $[S_N(0) \ S_B(0) \ S_F(0)] = [1 \ 0 \ 0]$, the three state probabilities $S_N(t_n)$, $S_B(t_n)$ and $S_F(t_n)$ from Equation (4.23) can be re-written as:

$$\begin{aligned} S_N(t_n) &= \prod_{i=0}^{t_n-1} \theta_{NN}(i) \\ S_B(t_n) &= \sum_{j=0}^{t_n-1} \left[\theta_{NB}(j) \cdot \prod_{i=1}^j \theta_{NN}(i-1) \right] \\ S_F(t_n) &= \sum_{j=0}^{t_n-1} \left[\theta_{NF}(j) \cdot \prod_{i=1}^j \theta_{NN}(i-1) \right] \end{aligned} \quad (4.24)$$

At t_{NB} , cluster moves to the *Backup* state with the state probability vector $\mathbf{Pr}(t_{NB}) = [S_N(t_{NB}) \ S_B(t_{NB}) \ S_F(t_{NB})]$. Assume that it stays in the *Backup* state for a duration of T_B time until time $t < t_{BF}$, and at t_{BF} the cluster goes to the *Fail* state, as in Figure 4.2. Again using Equation (4.19), for the duration of T_B , with the given initial vector for *Backup* state, $\mathbf{Pr}(t_{NB})$, we can find the first state probability vector $\mathbf{Pr}(t_{NB}+1)$ after time t_{NB} , as given below:

$$\mathbf{Pr}(t_{NB}+1) = \mathbf{Pr}(t_{NB}) \cdot \Delta(t_{NB})$$

$$= \begin{bmatrix} S_N(t_{NB}) & S_B(t_{NB}) & S_F(t_{NB}) \end{bmatrix} \bullet \begin{bmatrix} \theta_{NN}(t_{NB}) & \theta_{NB}(t_{NB}) & \theta_{NF}(t_{NB}) \\ 0 & \theta_{BB}(t_{NB}) & \theta_{BF}(t_{NB}) \\ 0 & 0 & 1 \end{bmatrix} \quad (4.25)$$

$$= \begin{bmatrix} S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NF}(t_{NB}) \\ + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BF}(t_{NB}) & + S_F(t_{NB}) \end{bmatrix}$$

Similarly $\mathbf{Pr}(t_{NB}+2)$ and $\mathbf{Pr}(t_{NB}+3)$ at $t = t_{NB}+2$ and $t = t_{NB}+3$ respectively can be given as

$$\mathbf{Pr}(t_{NB}+2) = \mathbf{Pr}(t_{NB}+1) \cdot \Delta(t_{NB}+1)$$

$$= \begin{bmatrix} S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NF}(t_{NB}) \\ + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BF}(t_{NB}) & + S_F(t_{NB}) \end{bmatrix} \bullet \begin{bmatrix} \theta_{NN}(t_{NB}+1) & \theta_{NB}(t_{NB}+1) & \theta_{NF}(t_{NB}+1) \\ 0 & \theta_{BB}(t_{NB}+1) & \theta_{BF}(t_{NB}+1) \\ 0 & 0 & 1 \end{bmatrix} \quad (4.26)$$

$$= \begin{bmatrix} S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) \cdot \theta_{NF}(t_{NB}+1) \\ \cdot \theta_{NB}(t_{NB}+1) & + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ \cdot \theta_{NN}(t_{NB}) & \cdot \theta_{BB}(t_{NB}+1) & + S_N(t_{NB}) \cdot \theta_{NF}(t_{NB}) \\ \cdot \theta_{NN}(t_{NB}+1) & + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BF}(t_{NB}) \\ & \cdot \theta_{BB}(t_{NB}+1) & + S_F(t_{NB}) \end{bmatrix}$$

$$\mathbf{Pr}(t_{NB}+3) = \mathbf{Pr}(t_{NB}+2) \cdot \Delta(t_{NB}+2)$$

$$= \begin{bmatrix} S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) & S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) \cdot \theta_{NF}(t_{NB}+1) \\ \cdot \theta_{NB}(t_{NB}+1) & + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ \cdot \theta_{BB}(t_{NB}+1) & + S_N(t_{NB}) \cdot \theta_{NF}(t_{NB}) \\ + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) & + S_B(t_{NB}) \cdot \theta_{BF}(t_{NB}) \\ \cdot \theta_{BB}(t_{NB}+1) & + S_F(t_{NB}) \end{bmatrix} \cdot \begin{bmatrix} \theta_{NN}(t_{NB}+2) & \theta_{NB}(t_{NB}+2) & \theta_{NF}(t_{NB}+2) \\ 0 & \theta_{BB}(t_{NB}+2) & \theta_{BF}(t_{NB}+2) \\ 0 & 0 & 1 \end{bmatrix} \quad (4.27)$$

$$= \begin{bmatrix} S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) \cdot \theta_{NN}(t_{NB}+1) \cdot \theta_{NF}(t_{NB}+2) \\ S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) \cdot \theta_{NB}(t_{NB}+1) \cdot \theta_{BF}(t_{NB}+2) \\ \cdot \theta_{NB}(t_{NB}+1) \cdot \theta_{NB}(t_{NB}+2) + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) \cdot \theta_{BB}(t_{NB}+1) \cdot \theta_{BF}(t_{NB}+2) \\ + S_N(t_{NB}) \cdot \theta_{NN}(t_{NB}) \cdot \theta_{NF}(t_{NB}+1) \\ \cdot \theta_{NN}(t_{NB}+1) + S_N(t_{NB}) \cdot \theta_{NB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ \cdot \theta_{NN}(t_{NB}+2) \cdot \theta_{BB}(t_{NB}+1) \cdot \theta_{BB}(t_{NB}+2) + S_B(t_{NB}) \cdot \theta_{BB}(t_{NB}) \cdot \theta_{BF}(t_{NB}+1) \\ + S_N(t_{NB}) \cdot \theta_{NF}(t_{NB}) \\ \cdot \theta_{BB}(t_{NB}+1) \cdot \theta_{BB}(t_{NB}+2) + S_B(t_{NB}) \cdot \theta_{BF}(t_{NB}) \\ + S_F(t_{NB}) \end{bmatrix}$$

Hence, at any time $t = t_{NB}+t_b$ during the period of T_B , we can find the three state probabilities $S_N(t_{NB}+t_b)$, $S_B(t_{NB}+t_b)$ and $S_F(t_{NB}+t_b)$ of the general state probability vector $\mathbf{Pr}(t_{NB}+t_b)$ as given below:

$$\begin{aligned}
S_N(t_{NB} + t_b) &= S_N(t_{NB}) \prod_{i=0}^{t_b-1} \theta_{NN}(t_{NB} + i) \\
S_B(t_{NB} + t_b) &= S_B(t_{NB}) \prod_{i=0}^{t_b-1} \theta_{BB}(t_{NB} + i) \\
&\quad + S_N(t_{NB}) \left\{ \sum_{j=0}^{t_b-1} \left[\theta_{NB}(t_{NB} + j) \cdot \prod_{i=1}^j \theta_{NN}(t_{NB} + i - 1) \right] \right. \\
&\quad \left. \cdot \prod_{i=1}^{t_b-j-1} \theta_{BB}(t_{NB} + t_b - i) \right\} \\
S_F(t_{NB} + t_b) &= S_F(t_{NB}) + S_B(t_{NB}) \left\{ \sum_{j=0}^{t_b-1} \left[\theta_{BF}(t_{NB} + j) \cdot \prod_{i=1}^j \theta_{BB}(t_{NB} + i - 1) \right] \right\} \\
&\quad + S_N(t_{NB}) \left\{ \sum_{j=0}^{t_b-1} \left[\theta_{NF}(t_{NB} + j) \cdot \prod_{i=1}^j \theta_{NN}(t_{NB} + i - 1) \right. \right. \\
&\quad \left. \left. + \sum_{i=1}^j \left[\theta_{BF}(t_{NB} + j) \cdot \theta_{NB}(t_{NB} + i - 1) \right. \right. \right. \\
&\quad \left. \left. \cdot \prod_{k=1}^{i-1} \theta_{NN}(t_{NB} + k - 1) \cdot \prod_{k=1}^{j-i} \theta_{BB}(t_{NB} + j - k) \right] \right] \right\}
\end{aligned} \tag{4.28}$$

Once the cluster enters the *Fail* state, then it stays there until the end of the round and the state probability vector $\mathbf{Pr}(t_f)$, at any time $t = t_f$, will be $[S_N(t_f) \ S_B(t_f) \ S_F(t_f)] = [0 \ 0 \ 1]$.

4.6 Numerical Analysis

The cluster model described above is mainly driven by two main probabilities, $\theta_{NB}(t)$ and $\theta_{BF}(t)$. $\theta_{NB}(t)$ reflects the chances of the cluster going into the *Backup* state due to the energy consumption of the CH, while $\theta_{BF}(t)$ indicates the chances of the cluster going into the *Fail* state due to the failure of the BCH. To demonstrate their impact on $S_N(t)$, $S_B(t)$ and $S_F(t)$, we calculated $\theta_{NB}(t)$ and $\theta_{BF}(t)$, with the help of Equations (4.11) and (4.12) at different times for a fixed number of sensor nodes in the cluster. We assume that the channel error probability, P_{error} , is 10^{-2} as in [ALK-05a]. With $\theta_{NB}(t)$, $\theta_{NF}(t)$ and $\theta_{BF}(t)$ available, we can have $\theta_{NN}(t)$ and $\theta_{BB}(t)$ from Equations (4.17) and (4.15), respectively. To illustrate the complete execution of the states of our Markov chain model, we chose the

initial energies of the CH and the BCH in such a way that they both were not able to complete the round, and eventually took the cluster in the *Fail* state.

Table 4.1 shows the calculated transition probabilities and the corresponding state probabilities obtained by using the Chapman-Kolmogorov equations. The output result conforms to the description of the BCH system. When the round starts with the cluster being in *Normal* state, the CH starts to lose the energy with time. At time t_{NB} , the cluster moves to the *Backup* state, and probability of the *Normal* state becomes zero. Once the cluster is in the *Backup* state, its probability also starts to decrease with the depletion of the BCH energy. At time t_{BF} , the cluster moves to the *Fail* state and its state probability becomes one. At all times the sum of the three state probabilities is always equal to one. We see that the number of transitions in the *Backup* state is more than the number of transitions in the *Normal* state. It is because the transition from the *Normal* to the *Backup* state occurs at a threshold level when some energy is left in the CH, while transition from the *Backup* to the *Fail* state occurs at complete energy depletion of the BCH node. Figure 4.3 shows the output curves of the three stationary probabilities for the whole round.

Table 4.1: State Probabilities with Respect to Different Values of $\theta_{nb}(t)$ and $\theta_{bf}(t)$

<i>Time</i>	$\theta_{NN}(t)$	$\theta_{NB}(t)$	$\theta_{BB}(t)$	$\theta_{BF}(t)$	$S_N(t)$	$S_B(t)$	$S_F(t)$
t_0	0.9818	0.0082	1	0	1	0	0
t_1	0.8835	0.1065	1	0	0.9818	0.0082	0.01
t_2	0.7572	0.2328	1	0	0.8674	0.1128	0.0198
t_3	0.6589	0.3311	1	0	0.6568	0.3147	0.0285
t_4	0.5325	0.4575	1	0	0.4327	0.5322	0.0351
t_5	0.4342	0.5558	1	0	0.2304	0.7302	0.0394
t_6	0.3161	0.6739	1	0	0.1001	0.8582	0.0417
t_7	0.2178	0.7722	1	0	0.0316	0.9257	0.0427
t_8	0.0915	0.8985	1	0	0.0069	0.9501	0.043
t_9	0.0013	0.9887	1	0	0.0006	0.9563	0.0431
t_{NB}	0.0013	0.9887	0.9937	0.0063	0	0.9569	0.0431
t_{NB+1}	0.0013	0.9887	0.9247	0.0753	0	0.9509	0.0491
t_{NB+2}	0.0013	0.9887	0.8313	0.1687	0	0.8793	0.1207
t_{NB+3}	0.0013	0.9887	0.756	0.244	0	0.7309	0.2691
t_{NB+4}	0.0013	0.9887	0.6787	0.3213	0	0.5526	0.4474
t_{NB+5}	0.0013	0.9887	0.5873	0.4127	0	0.375	0.625
t_{NB+6}	0.0013	0.9887	0.51	0.49	0	0.2202	0.7798
t_{NB+7}	0.0013	0.9887	0.4186	0.5814	0	0.1123	0.8877
t_{NB+8}	0.0013	0.9887	0.3413	0.6587	0	0.047	0.953
t_{NB+9}	0.0013	0.9887	0.2561	0.7439	0	0.016	0.984
t_{NB+10}	0.0013	0.9887	0.1726	0.8274	0	0.0041	0.9959
t_{NB+11}	0.0013	0.9887	0.0874	0.9126	0	0.0007	0.9993
t_{NB+12}	0.0013	0.9887	0.0164	0.9836	0	0.0001	0.9999
t_{BF}					0	0	1

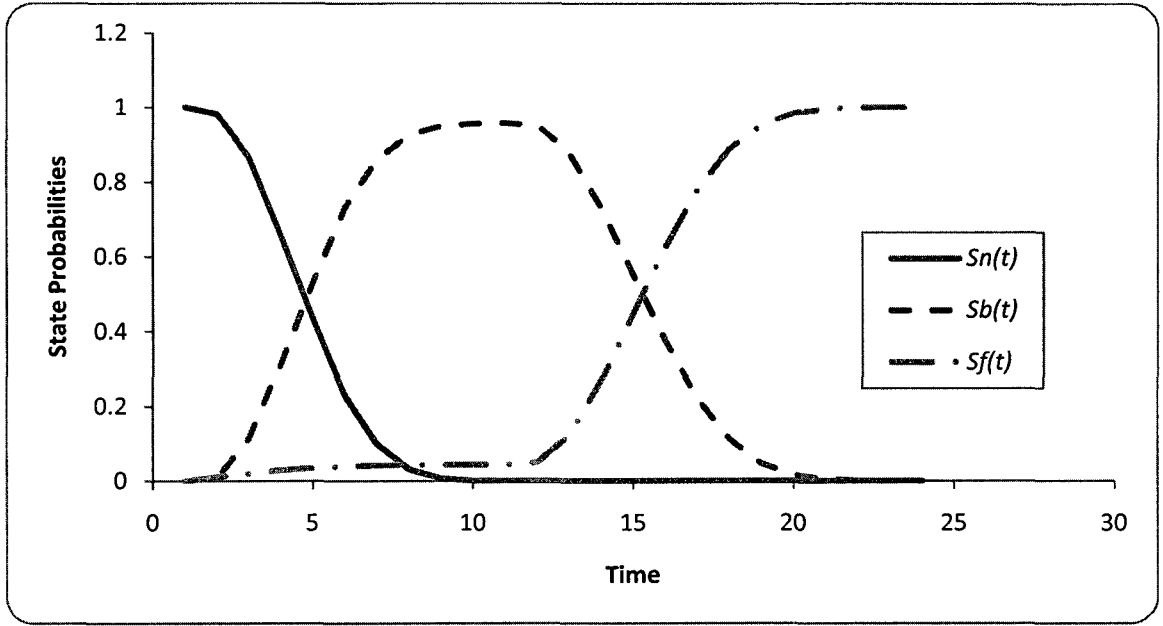


Figure 4.3: The stationary probabilities of *Normal*, *Backup* and *Fail* states during a complete round

It is very evident that if there were no BCH then the cluster would go in the *Fail* state very early and leave the cluster in nonmonitoring state for the rest of the period. The implementation of the BCH has delayed the cluster failure and has increased the cluster reliability. This reliability model can be applied to any three-state fault-tolerance system having varying transition probabilities and a given initial state probability vector.

4.7 Summary

In this chapter, we have presented the cluster reliability model of the BCH-based clustered WSN, using the Markov chain model. We have used a non-homogeneous Markov process and have adopted the Forward Chapman-Kolmogorov equations to compute the cluster states in a finite three state space model. The cluster reliability is the function of the energy of the CH and the BCH. If in a cluster, the selected CH is not able to complete the round and other sensor nodes' residual energies are also less than the CH, then a BCH will help to increase the cluster reliability.

The accuracy of the model has been tested by obtaining the probabilities of the CH and

the BCH going towards the failure, at different times, for a fixed number of sensor nodes and applying on the presented model. The results obtained show that the proposed model has been able to accurately match the behaviour of the cluster state transition. The presented model can be applied to any three-state fault-tolerance system with varying transition probabilities and a given initial state probability vector.

Chapter 5

An Efficient MAC Scheme with Dynamic Slot Assignment

5.1 *Introduction*

It is of vital importance to focus on preserving sensor nodes' energy while designing any protocol for a WSN (Wireless Sensor Network). In the sensor nodes, wireless radio is the most energy consuming unit. At any time during the sensor activity, the radio can be either in transmit state, receive state or idle state. All these states consume almost the same amount of energy, except if they are in sleep mode [ALI-08]. The MAC (Medium Access Control) layer comes into play that dictates the use of this resource. An efficient MAC layer protocol is required to conserve the radio energy while accessing the channel and coordinate the access of the sensor nodes to the shared wireless medium. The MAC layer provides precise control of the transceiver in order to turn the wireless radio ON or OFF. While controlling the transceiver, an efficient MAC layer protocol is the one that maximizes the sleep period of the node, while preserving the highest throughput, the minimum latency, and the maximum energy conserving in a WSN.

Here we propose a cluster-based dynamic TDMA MAC layer scheme that meets the above mentioned criteria and preserves the overall sensor network energy. This scheme exploits the resourceful sensor nodes that have dual channel or dual band transceivers, which is now becoming available in the sensor nodes [RUZ-06]. In this scheme, one channel is reserved for transmitting and receiving control signals while the other channel

is for the normal data transfer [HAS-10b].

This scheme is targeted towards applications with low activity sensor network where the sensor nodes encounter inconsistent and non-deterministic events. The protocols which are targeted for periodic data transmission are inefficient in terms of energy conservation and bandwidth utilization for low activity sensor network [HUS-09], [LI-04].

5.2 Problem Definition

5.2.1 Pure TDMA-based MAC

TDMA-based MAC scheme is mostly used in the cluster-based two-tier networks, where the sensor nodes in a cluster send their data to a designated CH. Most of the suggested works that use TDMA-based MAC scheme assumed that the sensor nodes have periodic data and event occurrence is deterministic. Hence, they assumed that there will be enough data to fill their transmission slots entirely and the transmission channel will always be busy, using the channel bandwidth efficiently. But there are many other applications where events take place non-deterministically with inconsistent activities in the network. This behaviour results in varying data traffic where many sensor nodes may or may not have the data to send. Assigning a time slot in a frame to a sensor node, which has no data to send, wastes the channel bandwidth and sensor node's energy. There may be other cases where some sensor nodes have more data to send than others due to high network activity in that region. Then the underutilization of these empty slots will be further discernible.

Here is a simple illustration to understand this problem. In conventional TDMA-based protocols, which are employed in a cluster-based network, every single sensor in the network is assigned a time slot to send its data. For example, if there are 100 sensor nodes in a network and 5 clusters are formed then 20 nodes will be in each cluster. Figure 5.1 gives an example of the cluster network.

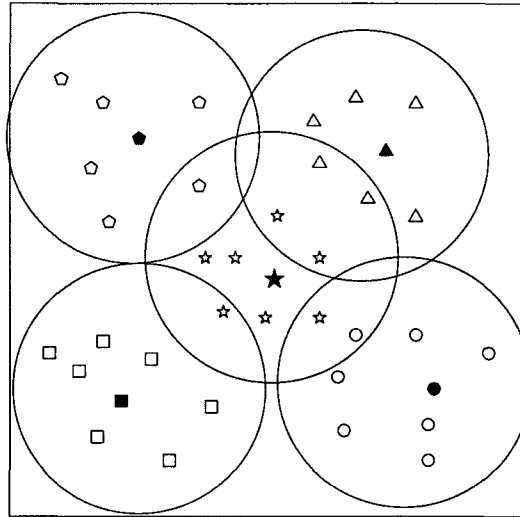


Figure 5.1: An illustration of a clustered network

If the network activity of the whole network is 30% or less, then 70% of the time slots will be empty. Some sensor nodes will have the data at one time and others will have at some other times. Figure 5.2 illustrates the state of the frames for the whole network of 5 clusters, with 30% activity. The figure shows the time slots of a frame in each cluster, where the slots with black shade are the occupied data slots while the rest of the slots are empty. It is obvious from the figure that this scheme will waste the energy and the channel bandwidth.

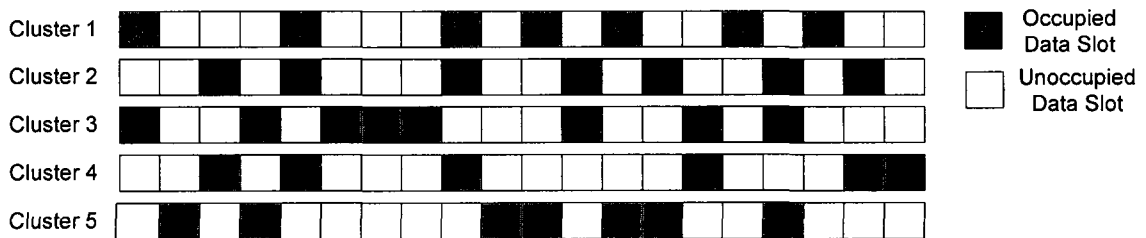


Figure 5.2: An illustration of network activity in a frame

5.2.2 Bit-Map-Assisted (BMA) MAC

The Bit-Map-Assisted (BMA) MAC protocol [LI-04] improves the above mentioned traditional TDMA schedule by incorporating a contention phase (CP) in the beginning of each TDMA frame, like in Figure 5.3.

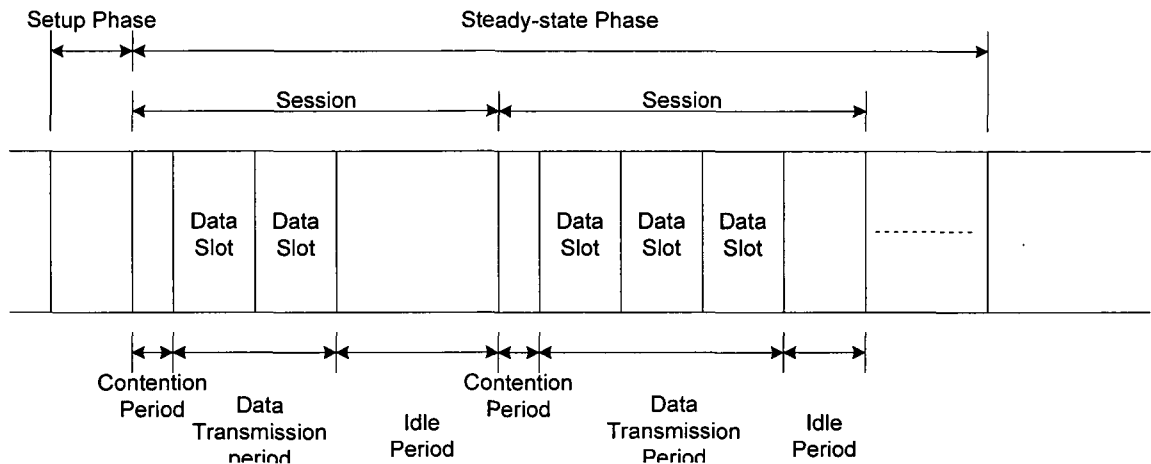


Figure 5.3: Illustration of a single round for BMA

In this contention phase before data messages, source nodes send 1-bit message to their CHs in order to reserve a data slot. Hence, the CHs know which members transmit in this frame and then allocate successive data slots to these source nodes. When the source nodes finish their transmission, the CHs go to sleep mode and become active in the next frame. As depicted in Figure 5.4, source node A, B and C transmit in the first three data slots and their CH enter into sleep state in the fourth data slot to avoid unnecessary energy wastage.

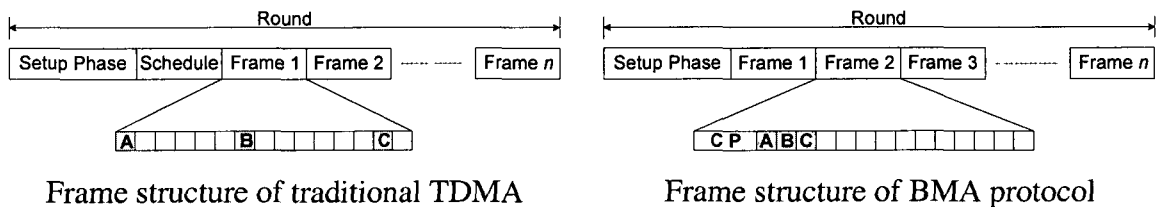


Figure 5.4: Frame structures of TDMA and BMA protocols

Although the energy is preserved by BMA but as the TDMA frames have the same length, it could not improve channel utility of the network. If the length of TDMA frame is constant, then during light network activity there will be empty slots in the frame. In addition, in BMA protocol the CHs broadcast a TDMA schedule packet in each frame. This packet introduces extra energy overhead. Broadcasting and receiving these schedule

packets consume considerable energy when the node density increases.

There are other similar efforts mentioned in the survey in Chapter 2 ([SHA-08], [BAR-07], [XIE-08], [FAN-07], [HUS-09]) that tried to address the given problem or improved the BMA protocol. However, they all more or less exhibit in the same way in terms of energy efficiency as compared to our proposal given next.

5.3 *Proposed Dynamic Slot Assignment (DSA) Scheme*

In order to resolve these issues, we propose Dynamic Slot Assignment (DSA) Scheme for cluster-based sensor networks, where the sensor nodes are densely deployed in the clusters, such that the CH of a cluster can accommodate only a subset of the sensor nodes in that cluster at a given time which should meet the network activity demand. This will save the wastage in channel bandwidth and minimize the sensors' energy consumption.

As in all the MAC schemes, the prime focus of the proposed scheme is to optimize the energy efficiency in low activity networks, where sensor nodes' activity is varying over the network region and the data traffic conditions are dynamic and changing. This MAC scheme requires all the sensor nodes to have dual channel or dual band transceivers. One transceiver is used for the control signalling on one channel and the other transceiver is used for the data traffic on the other channel, as shown in Figure 5.5.

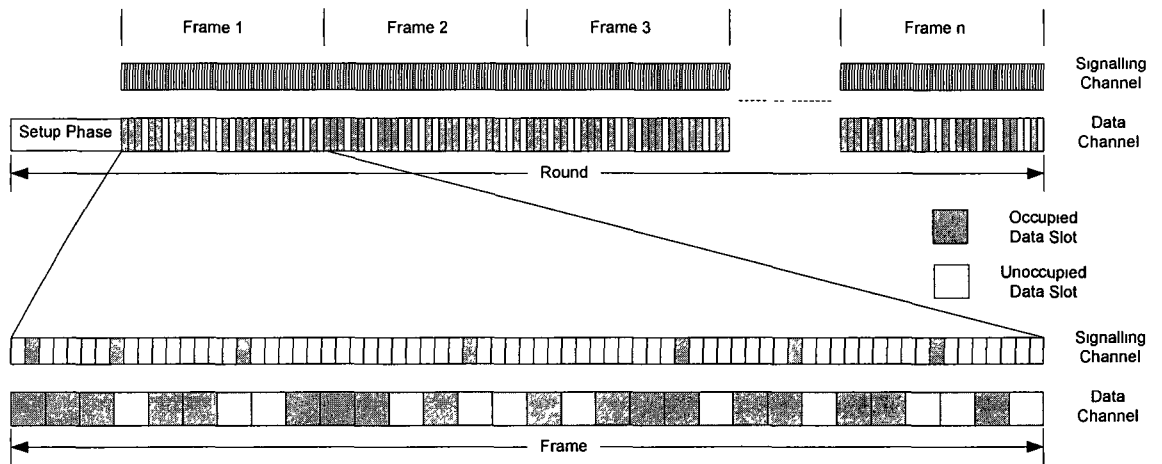


Figure 5.5: Illustration of a single round in DSA

We assume a large number of sensor nodes in a single cluster area, sensing the events. When there is any activity in a region of a cluster, then the sensor nodes of that region communicate with the CH of that cluster and send a request for connection on the signalling channel. The CH in return establishes the connection with the requesting node and assigns the next available time slot in the TDMA frame in the traffic channel. Once the gathered data is transmitted, the sensor node informs the CH and drops the connection with the CH. Hence, this model embraces the challenge of channel efficiency in a network, where simultaneously a cluster of the network may have a low activity and a high activity region.

5.4 **Assumptions**

We have made the following assumptions for the WSN we are considering for our MAC scheme:

1. All the sensor nodes have dual-band/dual channel transceivers.
2. The sensor nodes are densely deployed, following a Uniform Distribution in a 2-dimentional space.
3. All the sensor nodes know the location of the BS (Base Station). The BS has no energy constraints and is considered a powerful node having enhanced communication and computation capabilities.
4. The sensor nodes can transmit data at variable power levels depending on the distance to the receiver.
5. A similar network operation model as in LEACH [HEI-00], HEED [YOU-04] is implemented here, which consists of rounds. Each round consists of a clustering phase followed by a data collection and aggregating phase.
6. The CH selection algorithm is not a focus of this work, so any algorithm can be employed from LEACH [HEI-00], HEED [YOU-04] or others given in the survey in Chapter 2.
7. The same energy model is employed as given in Chapter 3, for the transmission of b -byte message over a distance d , as given below:

$$E_{Tx} = bE_{proc} + b\epsilon_{fs}d^2 \quad \text{for } 0 \leq d \leq d_{crossover} \quad (5.1)$$

$$E_{Tx} = bE_{proc} + b\epsilon_{mp}d^4 \quad \text{for } d \geq d_{crossover} \quad (5.2)$$

The energy consumed in receiving b -byte message is given by

$$E_{Rx} = bE_{proc} \quad (5.3)$$

where E_{proc} is the sensor's processing energy, depends on factors such as the digital coding, modulation, and filtering of the signal before it is sent to the transmitting amplifier.

The first assumption is reasonable as the recent advances in radio hardware manufacturing enabled the development of a low-cost and low-energy transceiver that can effectively receive on two parallel frequencies with a relatively small increase of energy consumption [RUZ-06]. An example is the nRF2401 transceiver [NRF-02] effectively employed on motes in [OFL-05], developed at the University of Cork, Ireland. The next 5 assumptions are very common in the sensor networks and are cited in most of the clustering protocols for data gathering applications, like in LEACH [HEI-00] and HEED [YOU-04] protocols. Assumption 7 is also reasonable given the sensor nodes transmit and receive at a fixed power level.

5.5 **System Model**

A simple system model is shown in Figure 5.6. When a sensor node or source node needs a time slot in the TDMA frame in the data channel, it sends a request packet on the signalling channel. This signalling channel is based on slotted ALOHA. The signalling channel consists of a number of signalling channel slots. A given request packet is first transmitted into a slot of signalling channel. If the request packet is unsuccessful due to any reason, then the same packet is transmitted into another slot of signalling channel. After a successful reception of a request packet through the signalling channel slot(s), the CH realizes that one sensor node requires radio resource to send data to the BS.

We consider a CH that can provide connections to a maximum of M sensor nodes, which are allowed to transmit data at a given time. The arrival of connection requests is assumed to be correlated Poisson distribution with a mean of λ . The number of slots in the

signalling channel, v , is three times the slots in the data channel i.e. $v = 3M$. It is selected this way because the signalling messages are smaller than the data messages, hence it can service more connection requests. The selection of a slot is random in nature. Therefore, the connection requests with Poisson arrival are distributed uniformly over the signalling channel slots that are also Poisson distributed. If the rejection of connection request-packets is negligible then we can assume that the output of each signalling channel slot is Poisson as well with a mean of S , as shown in Figure 5.6 (same as the slotted ALOHA throughput or output). Since the addition of Poisson arrivals is also Poisson, the overall output of the signalling channel (which is also the input of the data channel) is also Poisson where the mean is the addition of ‘multiple-output means’ corresponding to each signalling channel slot.

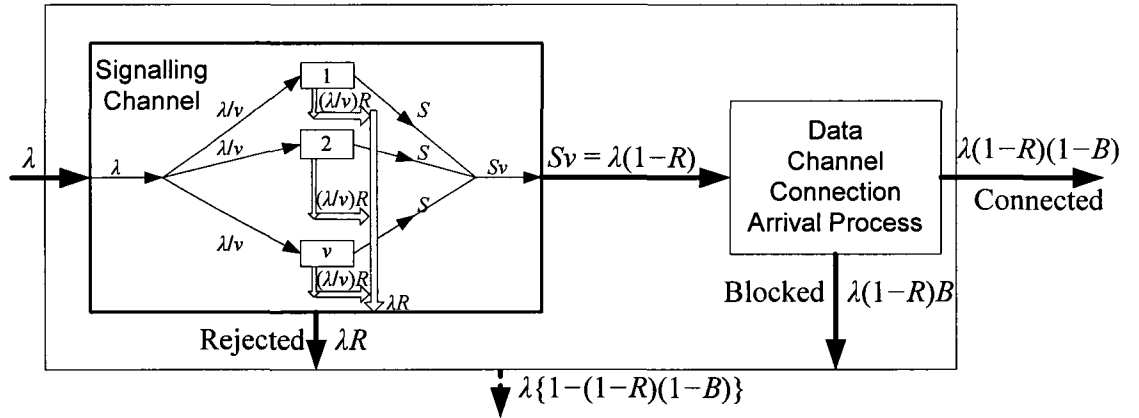


Figure 5.6: DSA system model

After a successful reception of a connection request-packet through the signalling channel (slots), the CH allocates a slot in the data channel for that sensor node to transmit its data, provided the CH has that slot available, and replies the sensor node with slot information in a connection reply message as shown in the sequence diagram Figure 5.7. The sensor node then sends the data until there is some activity in that region. Once the activity disappears and the sensor node has no more data to send, it then informs the CH that it is sending the last packet and drops the connection.

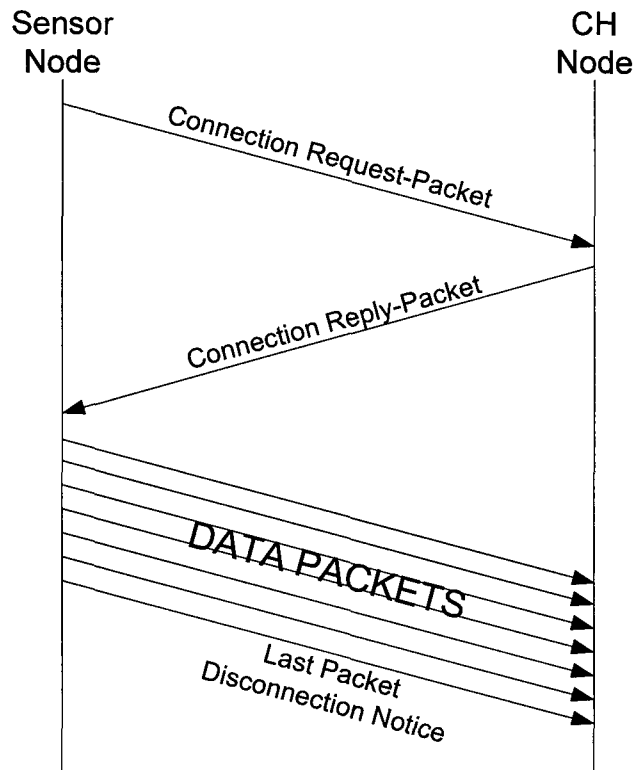


Figure 5.7: DSA sequence diagram for a connection request and data transmission from one sensor node

Depending on the data channel slots reservation, the CH may turn ON or OFF its radio, which saves its energy that could be consumed in idle listening. The signalling channel however needs to be monitored all the time to hear any connection request-packet, and the energy would be wasted if the radio were ON for the whole length of the round. To deal with this issue, the CH monitors the signalling channel at the beginning of every signalling channel slot for a portion of the slot in which it can hear the connection requests. If it hears any activity and receives any request-packet from its cluster's sensor nodes, then it will continue and transmit the channel assignment packet to that sensor node. If there is no activity then it will turn OFF its radio for the rest of the time slot. Hence, it saves the energy from idle listening of the signalling channel.

Here only one CH provides the services to a large number of sensor nodes in a single cluster, instead of many CHs in many clusters, hence the CH responsibilities of all are now fulfilled by that one CH alone. In every frame, energy is dissipated by many CHs in

data aggregation and then in sending the aggregated data towards the BS, now it is done by only one CH. The sensor network thus saves a lot of energy with this dynamic slot scheduling. At the same time, this MAC scheme also increases the channel utilization. The time slots in a frame are only assigned to those sensor nodes which have data to send, and slots are reserved by the sensor nodes as long as they need it. Once all the data are sent, the time slot is available again for the other sensor nodes.

But as mentioned earlier, the DSA MAC scheme is proposed for a low activity network. If at any time the network activity increases, then there will be more simultaneous connection-request packets, causing collision and rejection of the packets with the rate $(\lambda/\nu)R$ in each signalling channel slot, as shown in Figure 5.6. Furthermore, the data channel will also be fully occupied and the sensor node will face channel blocking with the rate B , which makes the overall system rejection and blocking rate $\lambda\{1-(1-R)(1-B)\}$.

5.6 *Traffic Model with Correlated Connection Arrival*

We consider a correlated or dependent Poisson connection arrival rate. We take event driven applications where occurrence of events generates the traffic. The first connection arrival from a sensor node is considered as a Poisson process and the second and following arrivals from other sensor nodes are correlated or dependent on the first arrival. For example, in a network for temperature monitoring, if there is an increase of temperature in one region of the network, then all close by sensor nodes will start to report this change. The same model can be used for mobility sensing networks.

We use Markov chains to model our system as it can describe our system, having correlated traffic model along with burstiness, reasonably well and it is mathematically tractable. Consider that a large number of sensor nodes can transmit their information to a CH. Assume that maximum number of slots in a TDMA frame is limited to n and is equal to the maximum number of connections that can be accepted by a CH in a cluster, which is M . The first connection request from the sensor nodes arrives at the CH with a Poisson arrival process with a mean rate λ , while the second and following requests arrive with a mean rate $x\lambda$, where $x \geq 1$ and is a correlation-factor that may vary with network applications. The connection duration of each sensor node is exponentially distributed

with a mean duration $1/\mu$. So the traffic intensity ρ for the sensor data traffic is λ/μ . The Markov chain model for the connection arrivals from the sensor nodes to a CH is shown in Figure 5.8.

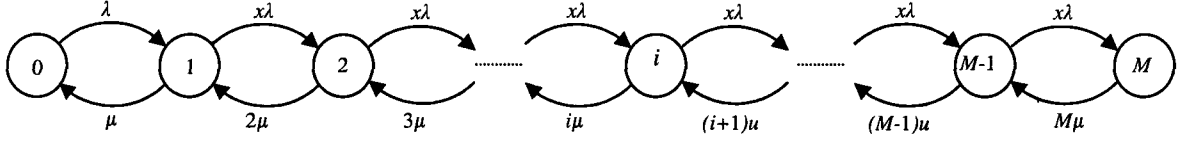


Figure 5.8: Markov chain model for data traffic

As there is a limited number of time slots available for the sensor nodes provided by the CH and the number of sensor nodes in a single cluster is more than the number of available time slots for a single TDMA frame, therefore there may be a time, when the connection requests come and are blocked due to unavailability of time slots.

For Poisson arrival model with given traffic intensity and steady state condition, the rate of change from the state i to state $(i+1)$ due to incoming connection requests is equal to the rate of change from state $(i+1)$ to state i due to dropping of connections. According to Figure 5.8, the probability that m sensor nodes are connected in a cluster and sending data to the CH, $P(m)$, can be derived by solving the Markov chain model. So starting from the left:

$$\lambda P(0) = \mu P(1) \quad \Rightarrow \quad P(1) = \frac{\lambda}{\mu} P(0) = \rho P(0) = \frac{1}{x} \frac{x\rho}{1!} P(0) \quad (5.4)$$

where ρ is the traffic intensity

$$x\lambda P(1) = 2\mu P(2) \quad \Rightarrow \quad P(2) = \frac{x}{2} \frac{\lambda}{\mu} P(1) = \frac{x}{2} \rho \frac{1}{x} \frac{(x\rho)}{1!} P(0) = \frac{1}{x} \frac{(x\rho)^2}{2!} P(0) \quad (5.5)$$

$$x\lambda P(2) = 3\mu P(3) \quad \Rightarrow \quad P(3) = \frac{x}{3} \frac{\lambda}{\mu} P(2) = \frac{x}{3} \rho \frac{1}{x} \frac{(x\rho)^2}{2!} P(0) = \frac{1}{x} \frac{(x\rho)^3}{3!} P(0) \quad (5.6)$$

$$x\lambda P(3) = 4\mu P(4) \Rightarrow P(4) = \frac{x}{4} \frac{\lambda}{\mu} P(3) = \frac{x}{4} \rho \frac{1}{x} \frac{(x\rho)^3}{3!} P(0) = \frac{1}{x} \frac{(x\rho)^4}{4!} P(0) \quad (5.7)$$

⋮

$$x\lambda P(i-1) = i\mu P(i) \Rightarrow P(i) = \frac{x}{i} \frac{\lambda}{\mu} P(i-1) = \frac{1}{x} \frac{(x\rho)^i}{i!} P(0) \quad (5.8)$$

⋮

$$x\lambda P(M-1) = M\mu P(M) \Rightarrow P(M) = \frac{x}{M} \frac{\lambda}{\mu} P(M-1) = \frac{1}{x} \frac{(x\rho)^M}{M!} P(0) \quad (5.9)$$

In general

$$P(m) = \begin{cases} P(0) & m = 0 \\ \frac{1}{x} \frac{(x\rho)^m}{m!} P(0) & 1 \leq m \leq M \end{cases} \quad (5.10)$$

$P(0)$ means the probability of no connection in the system and can be calculated by using law of conservation, i.e.,

$$P(0) + P(1) + P(2) + \dots + P(i) + \dots + P(M) = 1 \quad (5.11)$$

$$\Rightarrow P(0) + \frac{1}{x} \frac{x\rho}{1!} P(0) + \frac{1}{x} \frac{(x\rho)^2}{2!} P(0) + \dots + \frac{1}{x} \frac{(x\rho)^i}{i!} P(0) + \dots + \frac{1}{x} \frac{(x\rho)^M}{M!} P(0) = 1 \quad (5.12)$$

$$\Rightarrow P(0) \left[1 + \frac{1}{x} \frac{x\rho}{1!} + \frac{1}{x} \frac{(x\rho)^2}{2!} + \dots + \frac{1}{x} \frac{(x\rho)^i}{i!} + \dots + \frac{1}{x} \frac{(x\rho)^M}{M!} \right] = 1 \quad (5.13)$$

$$\Rightarrow P(0) \left[1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!} \right] = 1 \quad (5.14)$$

$$\Rightarrow P(0) = \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \quad (5.15)$$

Therefore, the probability that m sensor nodes are connected in a cluster and sending data to the CH is:

$$P(m) = \begin{cases} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} & m = 0 \\ \frac{\frac{1}{x} \frac{(x\rho)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} & 1 \leq m \leq M \end{cases} \quad (5.16)$$

5.7 Energy Consumption Model

Here we derive the energy consumption model for our DSA scheme. But before doing that, first we write the model for general TDMA-based network and then modify it according to the condition of low network activity. We also write the energy model for BMA protocol as given in [LI-04] for comparison purpose.

5.7.1 Energy Consumption Model for Existing Cluster-Based Networks

Here we put the energy consumption model for a general cluster-based sensor network. As mentioned earlier, in clustered sensor networks generally there are phases in a round: clustering setup-phase, when the clusters are formed, TDMA slot assignment phase and steady state phase, when normal data transmission occurs. The energy is consumed in all the phases, but the focus of this work is to minimize the energy loss in the data transmission phase, so we model the energy consumption during the slot assignment and data transmission phases only.

We consider a cluster-based network model with multiple clusters and their CHs.

Assume there are N sensor nodes distributed uniformly in a $U \times U$ region with C clusters and C CHs, so there are on an average $w = \frac{N}{C}$ sensor nodes per cluster. Each cluster has a CH that receives the data from other sensor nodes in that cluster, aggregates the data and then transmits to the BS. The similar computation and communication energy models are given in Chapter 3.

Assume the distance between the sensor node and its CH is less than the crossover distance, so the energy dissipation by a sensor node or a CH, transmitting data to each other follows the Friss free-space model (i.e. d^2 power loss). For transmitting 1 byte, $E_{SN \leftrightarrow CH}$ is given by:

$$E_{SN \leftrightarrow CH} = E_{proc} + \varepsilon_{fs} d_{CH}^2 \quad (5.17)$$

where, d_{CH} is the distance from the sensor node to the CH and E_{proc} is the sensor node's energy consumption for 1-byte data processing, which depends on factors such as the digital coding, modulation, and filtering of the signal before it is sent to the transmitting amplifier. Almost the same amount of energy is consumed for receiving 1-byte data by a sensor node or CH.

The area occupied by each cluster is approximately U^2/C , which is generally an arbitrary-shaped region with a node distribution $\sigma(x, y)$. If a CH is assumed to be at the center of the cluster, then the expected squared distance from the sensor nodes to the CH is given by:

$$E[d_{CH}^2] = \iint (x^2 + y^2) \sigma(x, y) dx dy = \iint r^2 \sigma(r, \theta) dr d\theta \quad (5.18)$$

If we further assume that this area is a circle with a radius of $U / \sqrt{\pi C}$ and $\sigma(r, \theta)$ is constant for r and θ , then Equation (5.18) is simplified to

$$E[d_{CH}^2] = \sigma R^4 / 2\pi C^2 \quad (5.19)$$

If the density of sensor nodes is uniform over the cluster area, then $\sigma = (1/(U^2/C))$. Hence,

$$E[d_{CH}^2] = U^2 / 2\pi C \quad (5.20)$$

Hence $E_{SN \leftrightarrow CH}$ becomes

$$E_{SN \leftrightarrow CH} = E_{proc} + \epsilon_{fs} U^2 / 2\pi C \quad (5.21)$$

Once the cluster is formed, the CH sends the TDMA schedule to each sensor node, using the information of its sensor nodes, gathered during cluster formation phase. The energy consumed by the CH in transmitting this control signal is:

$$E_{CHc} = sE_{SN \leftrightarrow CH} \quad (5.22)$$

where s is the number of bytes in the control message.

The BS is assumed to be away from the sensor nodes, and the distance to the BS is presumably greater than the cross-over distance, so the energy dissipation by a CH for transmitting 1 byte to BS follows the two-ray ground model (i.e. d^4 power loss), and it is given by:

$$E_{CH \rightarrow BS} = E_{proc} + \epsilon_{mp} d_{BS}^4 \quad (5.23)$$

Each CH also dissipates energy while receiving data from the sensor nodes, aggregating the received data, and transmitting the aggregated data to the BS. The energy consumption by a CH during a single frame for processing b -byte packets is given as:

$$E_{CH} = wbE_{proc} + wbE_{agg} + bE_{CH \rightarrow BS} \quad (5.24)$$

where E_{agg} is the energy needed to aggregate the data message, w is the average number of sensor nodes in a cluster and b is the number of bytes in each data packet.

Now in the case of non-CH sensor nodes, they receive s -byte TDMA schedule from the CH in every round and transmit b -byte data to the CH in f frames of each round. Thus, the energy used by each non-CH sensor node per round is:

$$E_{SN} = sE_{proc} + f bE_{SN \leftrightarrow CH} \quad (5.25)$$

So in a complete round consisting of ' f ' frames, energy dissipated by all the sensor nodes in a single cluster is

$$E_{clus/round} = E_{CHc} + f E_{CH} + wE_{SN} \quad (5.26)$$

and the total energy dissipated during a round by all the N sensor nodes in the network is

$$E_{total} = C * E_{clus / round} = E_{CHc} + CfE_{CH} + NfE_{SN} \quad (5.27)$$

5.7.2 TDMA Model with Low Network Activity

Equation (5.27) represents the energy model generally used in the conventional TDMA based protocols, where all the sensor nodes are considered to have data all the time to send. They assumed that the network activity is 100% and every sensor node has data to send to its respective CH in every frame. For networks with less activity, we define network activity factor ‘ α ’ which varies from 0 to 1. When a sensor node has no data to send, then its transceiver stays ON and idle in the time slot the sensor is assigned, consuming E_{idle} energy for the period of time slot T_s . The same happens with the CH, which keeps its radio ON and stays idle while receiving nothing. For the case when α is less than 1, the above energy model is modified as given below. The CH energy consumed in a single frame is

$$E_{CH} = wbE_{proc} + \alpha w b E_{agg} + bE_{CH \rightarrow BS} \quad (5.28)$$

The cluster energy for a single frame becomes

$$E_{clus} = \alpha w b E_{SN \leftrightarrow CH} + 2(1 - \alpha) w E_{idle} T_s + \alpha w b E_{proc} + \alpha w b E_{agg} + E_{CH \rightarrow BS} \quad (5.29)$$

The energy consumed in a complete round with f frames for a single cluster is

$$E_{clus / round} = E_{CHc} + f * E_{clus} \quad (5.30)$$

Hence the total energy for C clusters

$$E_{tdma} = C * E_{clus / round} \quad (5.31)$$

5.7.3 Energy Consumption Model for BMA MAC

In the BMA MAC protocol, during the steady state phase, there is a contention period (CP) of time T_c , before every frame, where sensor nodes have pre-assigned specific slots to send 1-bit control messages to inform their CHs whether they have data to transmit or not. The CH then sends the TDMA schedule for those sensor nodes having data, called source nodes. During CP all the nodes keep their radio transceivers ON. When the data transmission period starts, the source nodes send their data at their newly assigned slots.

When the source nodes finish their transmission, the CHs go to sleep mode and become active in the next frame.

So the energy consumption by every source node in a single frame for sending 1-bit control message during the CP, idle listening in the rest of the CP, receiving TDMA schedule from the CH and sending data to the CH, is given by:

$$E_{SrcN} = E_{SN \leftrightarrow CH} + (w-1)E_{idle}T_c + sE_{proc} + bE_{SN \leftrightarrow CH} \quad (5.32)$$

The non-source nodes consume energy only in the CP for idle listening:

$$E_{NSN} = wE_{idle}T_c + sE_{proc} \quad (5.33)$$

With network activity factor α , the CH of one cluster in any frame, receives slot request and data from αw sources and stay idle and in sleep mode in rest of the CP and data phase respectively. Hence energy dissipated by a CH during a single frame is

$$E_{CH} = \alpha w(s+b)E_{proc} + sE_{SN \leftrightarrow CH} + (1-\alpha)wE_{idle}T_c + \alpha w b E_{agg} + E_{CH \rightarrow BS} \quad (5.34)$$

So the energy consumed during one frame by all the sensor nodes of one cluster is

$$E_{clus} = \alpha w E_{SrcN} + (1-\alpha)w E_{NSN} + E_{CH} \quad (5.35)$$

The energy consumed in a complete round with f frames for a single cluster is

$$E_{clus/round} = f * E_{clus} \quad (5.36)$$

Hence the total energy for C clusters

$$E_{bma} = C * E_{clus/round} \quad (5.37)$$

5.7.4 Energy Model for Dynamic Slot Assignment (DSA) MAC

In our DSA model, we have to consider the energy consumption by the sensor nodes and the CH on the two channels, the signalling channel and the data channel. In every frame, the sensor nodes in the cluster send connection-request packets to the CH at the rate of λ packets per frame and after getting the connection or the time slot in the data channel they stay connected at an average for $1/\mu$ frames. So from Equation (5.16), using the probability of m sensor nodes being connected in a cluster, we can find the average

number of sensor nodes connected out of M possible connections in every frame:

$$m_{ave} = \sum_{m=1}^M mP(m) \quad (5.38)$$

$$\Rightarrow m_{ave} = \sum_{m=1}^M m \frac{\frac{1}{x} \frac{(x\rho)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \quad (5.39)$$

From Equation (5.39) following can be derived. For details of derivation, Appendix A can be referenced.

$$\Rightarrow m_{ave} = x\rho \left[1 - \frac{1 - \frac{1}{x} + \frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \right] \quad (5.40)$$

As the activity of the network is considered low and there are enough slots available in the signalling channel for taking on sensors' request-packets arrival rate, we assume there is no collision on the signalling channel.

As given earlier, $E_{SN \leftrightarrow CH}$ and E_{proc} are the energy consumed by the sensor nodes for transmitting and receiving 1 byte, respectively. Every sensor node consumes energy on the signalling channel for sending a request packet of r bytes, and for receiving the control packet of s bytes from the CH. Then it sends at an average $1/\mu$ data packets of b bytes on the data channel in $1/\mu$ consecutive frames. So each sensor node at an average will consume:

$$E_{SN} = rE_{SN \leftrightarrow CH} + sE_{proc} + bE_{SN \leftrightarrow CH} / \mu \quad (5.41)$$

The CH consumes energy in receiving the connection-request packets on the signalling channel at an arrival rate of λ packets per frame, and the same number of control packets is sent to each requesting sensor node. In the signalling channel, the number of slots for receiving requests is assumed to be three times the number of slots available in the data channel. So on the signalling channel, the CH keeps its radio ON for a portion of the slot in which it can hear the connection requests. If it hears any activity and receives any

request-packet from its cluster sensor nodes, then it will continue to listen and transmit the channel assignment packet to that sensor node. If there is no activity then it will turn OFF its radio for the rest of the time slot. Hence, it will consume energy in idle listening E_{idle} , equivalent to r bytes of data in $(3M - \lambda)$ slots. On the data channel, at an average the CH receives m_{ave} b -byte packets per frame from m_{ave} connected sensor nodes given in Equation (5.40). So on the data channel, the CH consumes energy $m_{ave} \cdot b \cdot E_{proc}$ for receiving m_{ave} b -byte packets per frame, energy $m_{ave} \cdot b \cdot E_{agg}$ for aggregating the same number of packets and then finally energy $E_{CH \rightarrow BS}$ for sending the aggregated packet to the BS. So E_{CH} can be given by:

$$E_{CH} = \lambda(rE_{proc} + sE_{SN \leftrightarrow CH}) + rE_{idle}(3M - \lambda) + m_{ave}(bE_{proc} + bE_{agg}) + E_{CH \rightarrow BS} \quad (5.42)$$

Hence, the total energy for the system in a single round for DSA scheme, with f frames in a round and m_{ave} sensor nodes sending data to the CH, can be given by:

$$E_{DSA} = m_{ave}E_{SN} + f * E_{CH} \quad (5.43)$$

5.7.5 Channel Utilization Model

In the DSA model, if m_{ave} is the average number of sensor nodes, sending data in a frame and M is the total number of slots, then channel utilization for the DSA scheme (ChU_{DSA}) can be given as

$$ChU_{DSA} = \frac{m_{ave}}{M} = \frac{x\rho}{M} \left[1 - \frac{1 - \frac{1}{x} + \frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \right] \quad (5.44)$$

where ρ is the traffic intensity within the network and is given as $\rho = \alpha * N$. The channel utilization for TDMA and BMA protocols will be the same as the network activity factor ' α '.

5.8 Numerical Analysis

We compare the performance of conventional TDMA, BMA, EA-TDMA and DSA as intra-cluster MAC schemes in terms of bandwidth utilization and energy consumption.

The results are based on numerical calculation. This comparison does not consider the data loss and corruption due to noisy channel, as it is not the scope of this work. Figure 5.9 illustrates the topology we have used for the comparison of the MAC schemes, with 100 sensor nodes and 5 clusters for BMA, EA-TDMA and TDMA, while only one cluster for the DSA scheme with the same number of nodes. The sensor deployment region is assumed 100m x 100m.

The BS is assumed to be located at $(x=50, y=175)$, i.e. 75 meters from the closest node. For the numerical analysis Table 5.1 shows the characteristics of the network and values of the parameters which are used in the energy models.

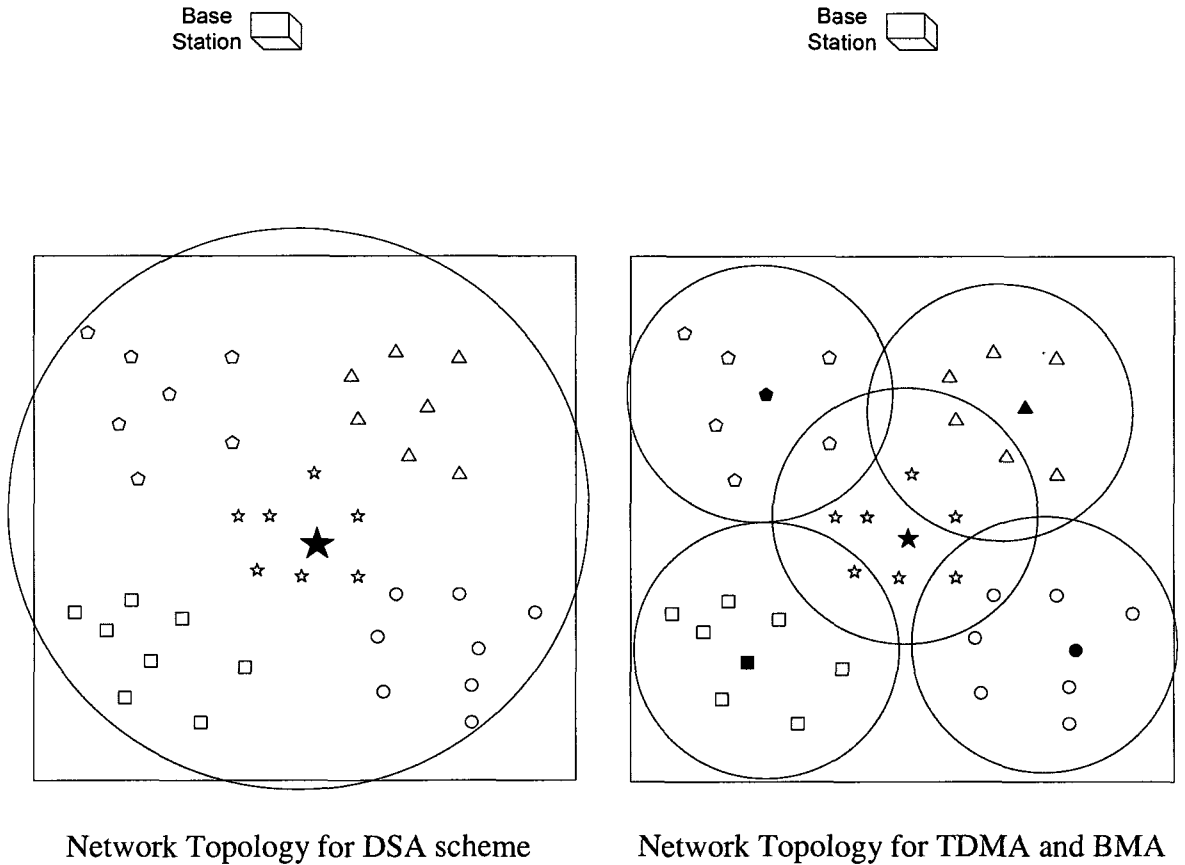


Figure 5.9: Network Topology used for the Numerical Analysis

Table 5.1: Characteristics of the Network for DSA Analysis

No. of nodes N	100 nodes
Network size, $R \times R$	100m x 100m
Number of clusters, C	5 clusters
Size of data packet, b	256 bytes-4kbytes
Size of control packet, r, s	15 bytes
Amplifier energy for free space model, ϵ_{fs}	10 pJ/bit/m ²
Amplifier energy for multipath model, ϵ_{mp}	0.0013pJ/bit/m ⁴
Sensor's processing energy, E_{rx}	50 nJ/bit
Sensor's transmitting energy, E_{tx}	55 nJ/bit
CH's aggregation energy, E_{agg}	5 nJ/bit
Distance to BS, d_{BS}	130m
No. of frames, f	30
Max. number of connected nodes in DSA, M	30

Figure 5.10 compares the channel utilization of the DSA model for different values of M with no correlation factor, i.e. $x=1$. Figure 5.10 shows that the traffic channel efficiency is very high with DSA scheme at low network activity, even with large number of available time slots. Whereas at high network activity, the DSA scheme starts blocking the channel as it can service only M number of connections while BMA or other TDMA MAC schemes continue to provide the service to the incoming requests.

Figure 5.11 compares the total energy consumption in a single round of four MAC schemes. As the available times slots, M is 30, after reaching 30% network activity, the DSA MAC scheme stops taking any more connections which keep the energy consumption at a constant level as compared to the other MAC schemes. But at low network activity, DSA outperforms all the MAC schemes. With high correlation factor, the DSA scheme saturates fast.

Figure 5.12 illustrates the comparison between 3 MAC schemes with respect to the arrival rate. Here it shows the clear performance of the DSA scheme, that the energy consumption is very low as compared to BMA and EA-TDMA. With high correlation factor in DSA, the channel slot occupancy saturates fast, but still it is energy efficient.

Figure 5.13 shows the impact of varying the data packet size on the energy consumption. With the network activity of 25% and keeping the holding time for transmitting 4 packets, the DSA model shows better performance over other MAC schemes with all packet sizes.

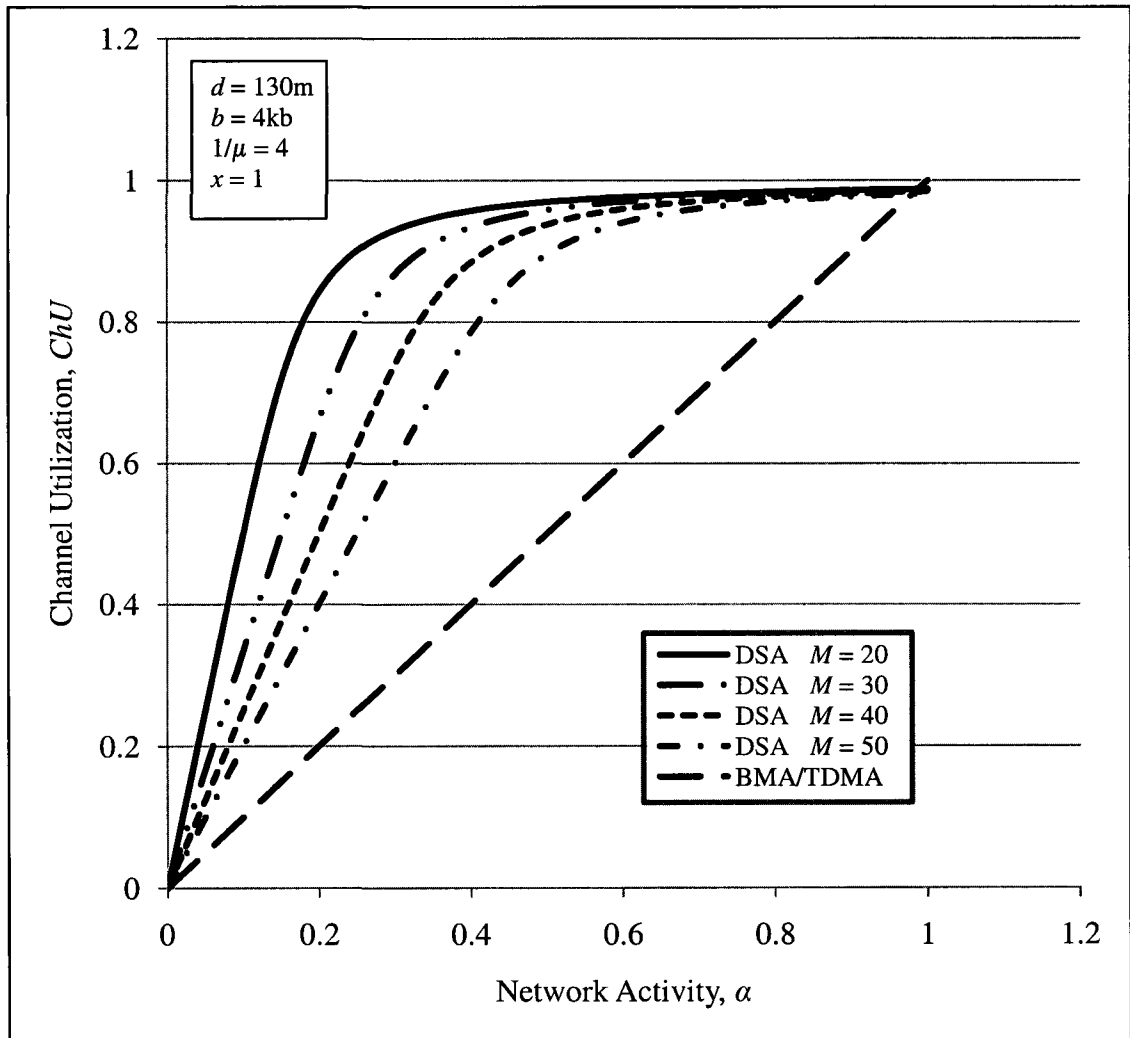
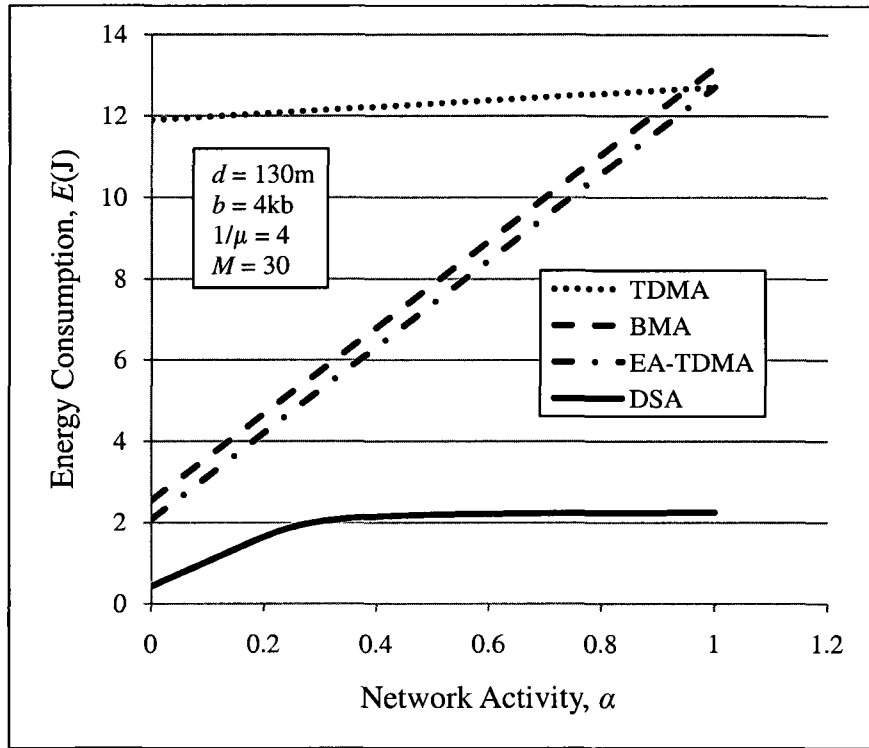
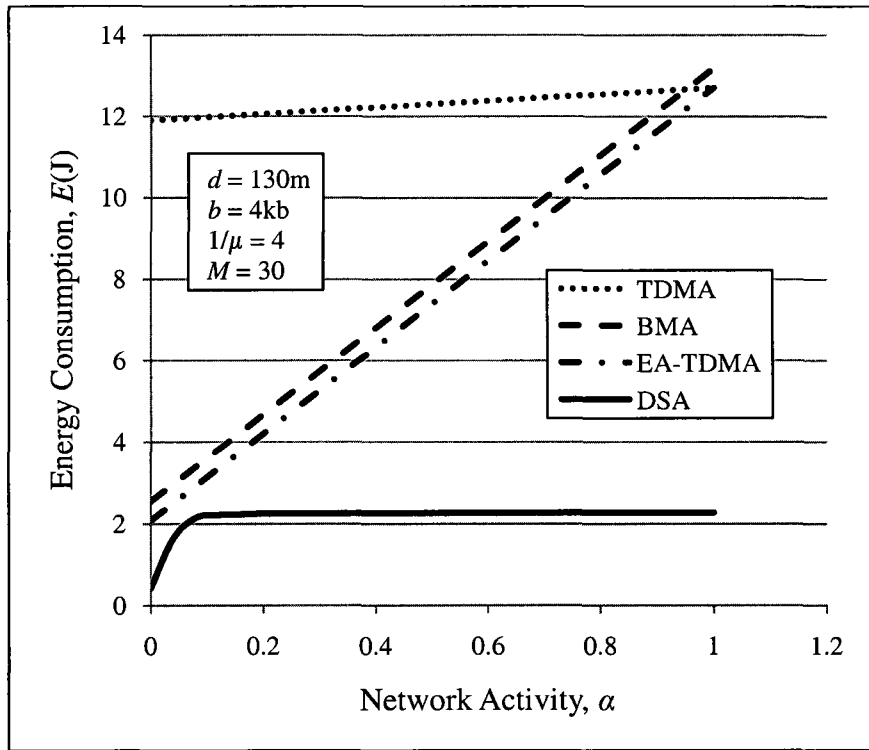


Figure 5.10: Channel Utilization w.r.t. network activity factor α in a single frame.

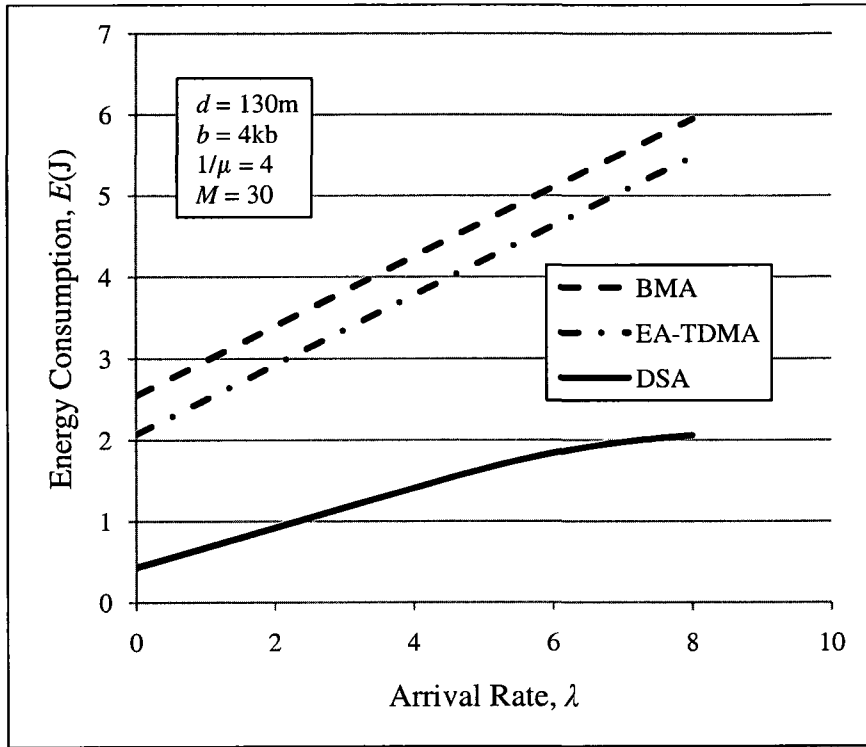


(a) $x=1$

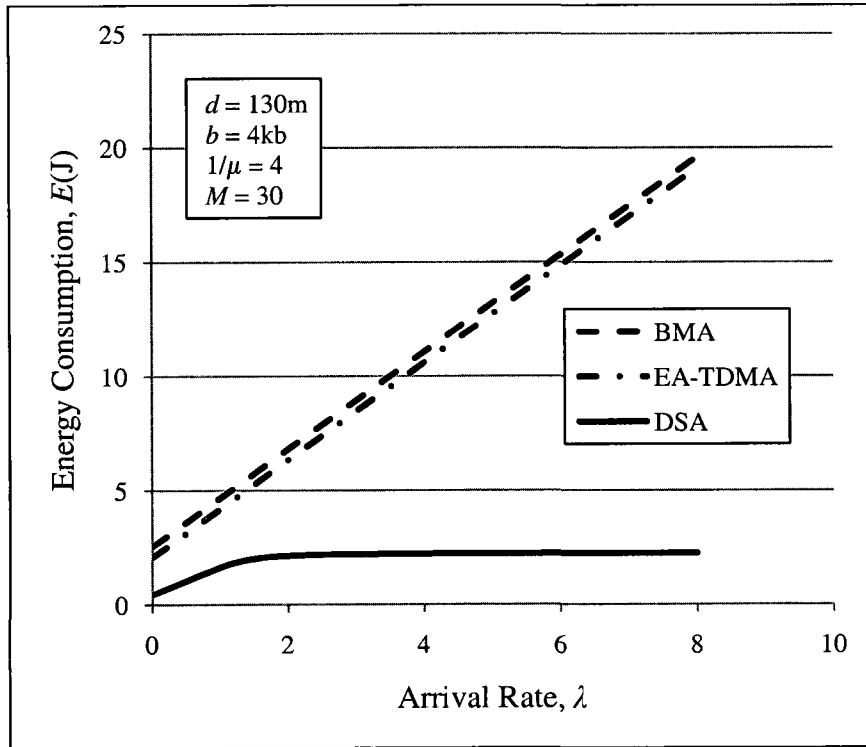


(b) $x=5$

Figure 5.11: Total Network Energy consumption w.r.t. network activity factor α , in a single round



(b) $x=1$



(a) $x=5$

Figure 5.12: Total Network Energy consumption w.r.t. arrival rate λ .

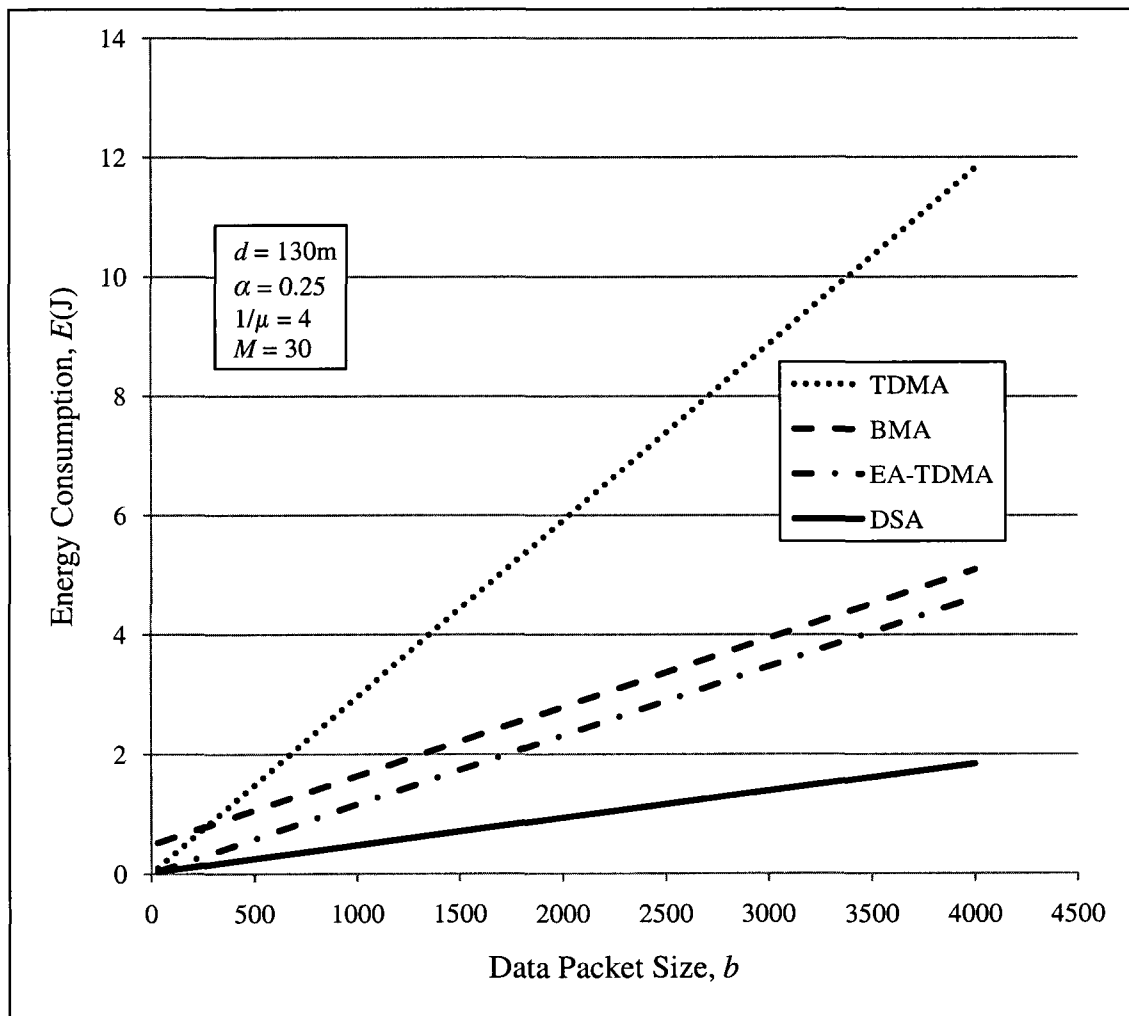


Figure 5.13: Energy Consumption w.r.t. to the data packet size.

5.9 ***Summary***

In this chapter, we have presented the DSA MAC scheme, an adaptive and dynamic TDMA slot scheduling model, where time slots are assigned to the sensor nodes on the fly, according to the need of the sensor nodes. The main goal of this study is to reduce the energy loss in the data transmission phase and minimize the wastage in channel bandwidth, in low activity networks with varying data traffic. We have also presented the system model and the analytical model of the proposed DSA scheme. We have validated the DSA model by numerical analysis and compared with the classical static TDMA scheme along with BMA and EA-TDMA protocols. The DSA performance surpasses all the MAC schemes significantly. The limitation of the proposed system is also stated here that the DSA protocol requires dual-band sensor nodes and its application is limited to low activity networks. In high activity networks, the DSA model may cause packet collision and channel blocking.

Chapter 6

MAC Scheme with Multislot Assignment and Slot-Stealing Method

6.1 *Introduction*

In this chapter, we present a novel analytical framework, Dynamic TDMA Slot Scheduling (DTSS), employed on top of the Dynamic Slot Assignment (DSA) scheme, proposed in Chapter 5, in order to enhance its performance. DTSS scheme [HAS-10a] is presented to analyze the channel utilization and packet dropping probability in bursty network environment under low and high traffic conditions with a large number of sensor nodes in a single cluster. DTSS scheme allows the network to adapt to the changing traffic load. Like in DSA, the connection is established between the CH and the sensor nodes based on the network activity, and requested number of TDMA slots is assigned to them dynamically.

We model the data traffic by a correlated stochastic process (i.e. Markov chain) for a network where the second and subsequent connection arrival rate is dependent on the first arrival rate. We numerically compare the DTSS with and without the enhancement, and prove significant improvement in the bandwidth efficiency and decrease in connection blocking probability in low activity networks. The drawback of the proposed system is also investigated. Results show that the efficiency of the MAC protocol can be increased significantly using the proposed model with reasonably low packet dropping probability.

6.2 ***Problem Definition***

As mentioned in Chapter 5, the DSA MAC scheme is proposed for low activity networks. If at any time the network activity increases, then there will be more incoming simultaneous connection-request packets, causing collisions and packet rejections in each signalling channel slot. Furthermore, the data channel will also be over occupied and the sensor node will face channel blocking, causing a high overall system rejection and channel blocking. It has been discussed in Section 5.5.

The DTSS scheme is proposed here to cope up with this situation by adding two features in the DSA model. First, it lets the sensor nodes to have more than one slot in a frame up to a defined maximum limit, so if they have a burst of data at any time then they can send them as quickly as possible. Second, it does allow slot-stealing which enables the system to reuse the unused slots which are already assigned to the sensor nodes and temporarily re-assigns them to the new requesting sensor nodes. These two enhancements to the DSA, alleviates the channel blocking to some extent but it does cause the packets to be dropped. Here we study both blocking probability and packet dropping probability along with bandwidth utilization.

6.3 ***Network Model***

6.3.1 **Basic Framework**

We consider the same framework of a cluster-based wireless sensor network, as given in Section 5.5. In summary, a CH is assigned to each cluster from among the sensor nodes. The sensor nodes are densely deployed in the clusters, such that the CH can accommodate only a subset of the sensor nodes in that cluster at a given time, which should meet the demand of network activity.

Assume that M is the maximum number of connections that can be accepted by a CH in a cluster. When any sensor node in the cluster has data to send, it sends a connection request to the CH on signalling channel to establish the connection. It also sends the number of time slots it may need to send its data. There are ' n ' time slots in a frame and the maximum number of slots that may be assigned to a sensor node is limited to ' q ',

where $q < n$. When the connection is established, the slots are assigned to the sensor node in the TDMA frame on the data channel. When the sensor node transmits all the data it gathered and has no more data to send and there is no further activity expected in that sensor region, then that sensor node terminates the connection.

6.3.2 Traffic Model with Correlated Connection Arrival

We consider the same correlated or dependent Poisson connection arrival model as considered for DSA protocol in Chapter 5, where the traffic is generated with the occurrence of events. We consider a large number of sensor nodes that can transmit their information to a single CH but a limited number of them can be connected at a time. When M is the maximum number of possible connections that the CH can offer, then the probability that m sensor nodes are connected out of M connections in the cluster and sending data to the CH is derived in Section 5.6 and is given as:

$$P(m) = \begin{cases} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} & m = 0 \\ \frac{\frac{1}{x} \frac{(x\rho)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} & 1 \leq m \leq M \end{cases} \quad (6.1)$$

The connection blocking probability $P(M)$, can also be obtained from Equation (6.1). If each sensor node occupies a maximum of one slot, then the probability that m sensor nodes occupy k slots is given by:

$$P(k | m) = \binom{m}{k} a^k (1-a)^{m-k} \quad (6.2)$$

where ‘ a ’ is the activity factor of the sensor nodes which is defined in the next section. However, each sensor node may send multiple packets in a bursty nature. Next, we discuss a general ON-OFF traffic model which is used later for Bursty Network Model.

6.3.3 General ON-OFF Traffic Model

A two state ON-OFF model is indicated in Figure 6.1. The transition occurs between states with geometrically distributed period in Bernoulli's fashion and independent of each other.

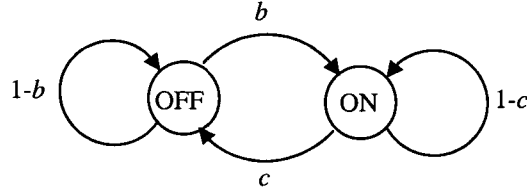


Figure 6.1: Two state ON-OFF traffic model.

The probability of state transition from ON state to OFF state after j time slots or from OFF state to ON state after k time slots is:

$$Q(j) = (1 - c)^{j-1} c \quad j \geq 1 \quad \text{or} \quad (6.3)$$

$$Q(k) = (1 - b)^{k-1} b \quad k \geq 1$$

The expected number of traffic (bursts) is:

$$E_B[j] = \sum_{j=1}^{\infty} jQ(j) = 1/c \quad \text{or} \quad (6.4)$$

$$E_S[k] = \sum_{k=1}^{\infty} kQ(k) = 1/b$$

where E_B and E_S are the probabilities of Expected Burst and Expected Silence. So the probability of the traffic generation by an ON-OFF traffic source is:

$$a = \frac{E_B[j]}{E_B[j] + E_S[k]} = \frac{b}{b + c} \quad (6.5)$$

where 'a' is the activity factor of sensor nodes.

6.3.4 Bursty Network Model

In a WSN when a particular area is generating data at a higher rate than others are, it causes a burst effect in the network, as has been considered in [KUM-08]. In many applications, the bursty traffic is found to be self-similar traffic like in typical MPEG-2 video applications [PAR-05] and other networking applications [SHU-99]. Self-similar traffic can be modeled by aggregating many ON-OFF message sources [PAR-05]. We did not use direct self-similar traffic because it will make the analysis more complex.

Consider the case where each sensor node has a q number of ON-OFF messages. In other words, one sensor node can occupy a maximum of q time slots per frame. According to Equation (6.1), m sensor nodes are connected. Therefore, all m sensor nodes can occupy a maximum of mq time slots, where $mq < n$ (maximum time slots in a TDMA frame are limited to n). Assume that the occupancy of each time slot is independent and the sensor nodes occupy the time slots with probability a , as described in Section 6.3.3. Therefore, the probability that m sensor nodes occupy k slots is given below:

$$P(k | m) = \binom{mq}{k} a^k (1-a)^{mq-k} \quad \text{where } 0 \leq k \leq mq \quad (6.6)$$

So we can use this model for self-similar traffic. The probability that all M sensor nodes occupy k slots is given by

$$P(k) = \sum_{m=\lceil k/q \rceil}^M P(k | m) P(m) \quad (6.7)$$

$$P(k) = \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m = 0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.8)$$

where the notation $\lceil z \rceil$ defines the smallest integer $\geq z$. The average number of slots occupied by all the sensor nodes can be obtained by

$$A = \sum_{k=0}^{Mq} kp(k) \quad (6.9)$$

$$A = \sum_{k=0}^{Mq} k \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m = 0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.10)$$

Finally, the traffic channel efficiency with many ON-OFF message sources is

$$E_1 = \frac{A}{n} = \frac{1}{n} \sum_{k=0}^{Mq} k \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m = 0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.11)$$

Consider a case where each frame consists of 30 slots, i.e. $n=30$. Each sensor node may be assigned a maximum of 3 slots per time frame, i.e. $q=3$. Therefore, without any packet dropping, we cannot allow more than 10 sensor nodes to be connected. We have analyzed the channel utilization and blocking probability for different values of M with correlation factor $x=5$ and no correlation, i.e. $x=1$. We kept the value of sensor activity factor, a , 0.2 and 0.5 to see the effect on channel utilization. Figures 6.2 and 6.3 show the traffic channel efficiency of one cluster. Figure 6.4 shows the connection blocking probability in a bursty WSN system.

Figure 6.2 shows that the traffic channel utilization is very low in the bursty WSN system with the activity factor set to 0.2. When the activity factor is increased to 0.5, the channel utilization also increased, but could only reach 50 percent as in Figure 6.3. With an increase in the correlation factor, we see that the channel utilization saturates to its peak value quickly. The connection blocking probability also goes high once it gets close to the system limit, as shown in Figure 6.4.

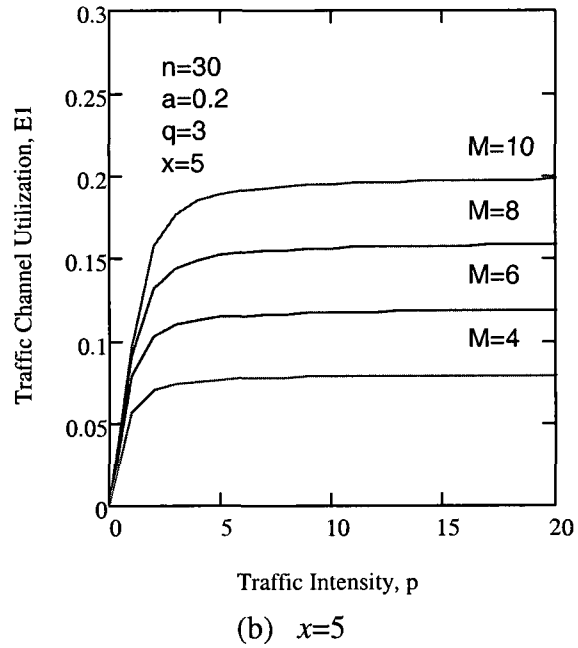
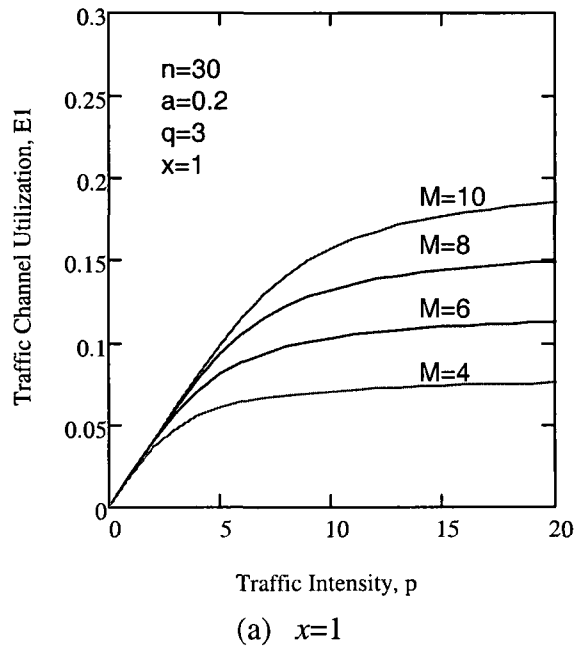
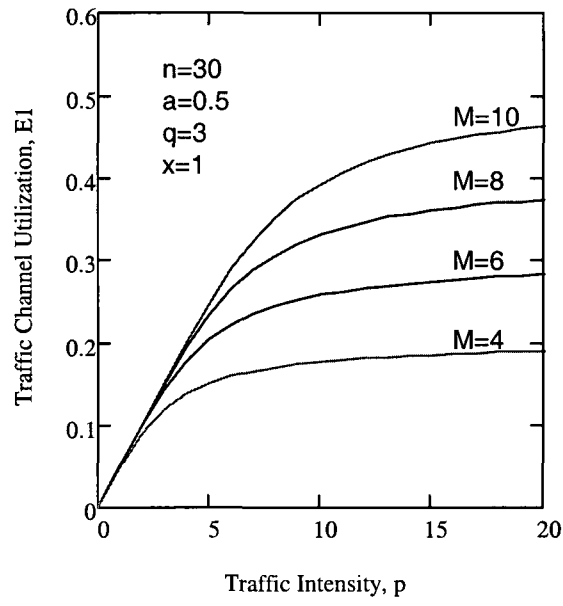
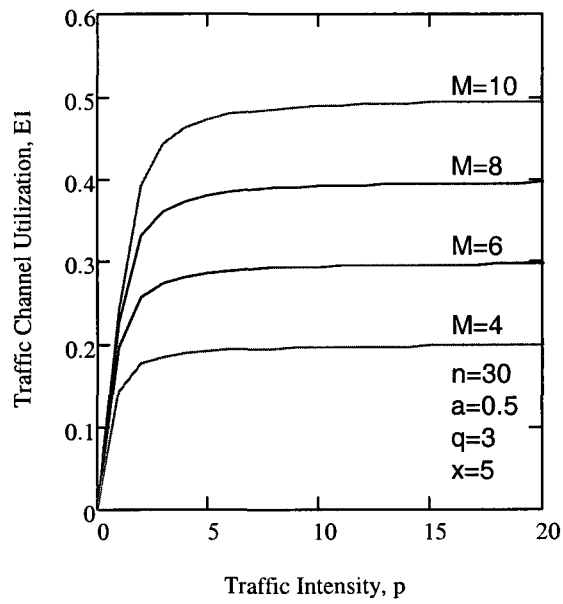


Figure 6.2: Traffic channel utilization in bursty network with $a = 0.2$

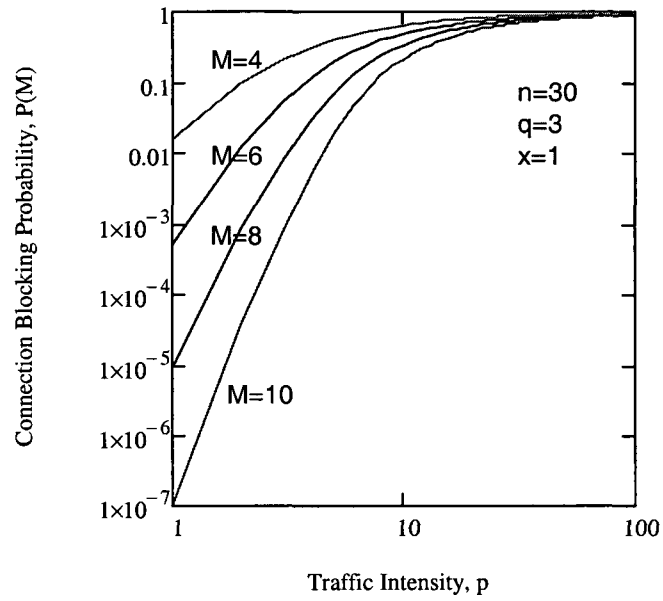


(a) $x=1$

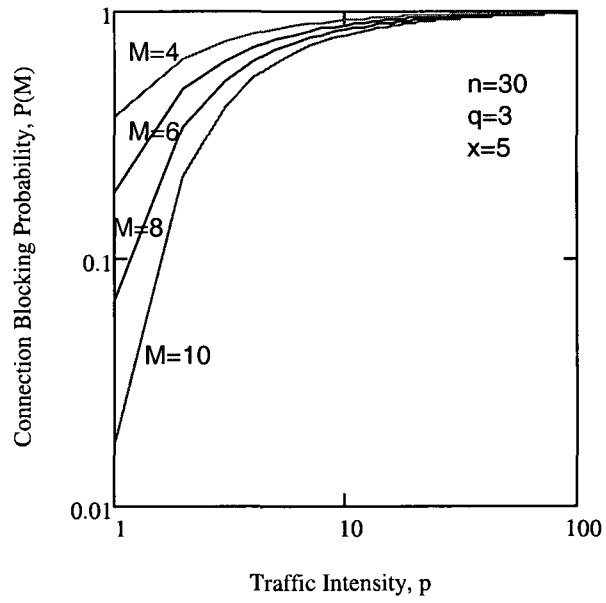


(b) $x=5$

Figure 6.3: Traffic channel utilization in bursty network with $a = 0.5$



(a) $x=1$



(b) $x=5$

Figure 6.4: Connection blocking probability $P(M)$ in bursty network

6.4 Formulation of the Proposed DTSS Model

In order to alleviate the connection probability issue and increase the channel utilization with low sensor activity factor, we propose to do slot-stealing and assign these stolen slots to the requesting sensor nodes for new connections. The slots are stolen from those sensor nodes which already had been assigned the data channel time slots. To execute this process, the CH monitors the activity of the connected sensor nodes. The sensor nodes which are found to have an activity factor less than a threshold value, for example below 50 percent, their slots are shared with the other requesting sensor nodes.

This will create a contention window between the two sensor nodes for that time slot. To avoid a possible collision, the newly assigned sensor node is notified that it has been assigned a stolen slot, and it needs to get a green signal from the CH by sending and receiving Request to Send (RTS) and Clear to Send (CTS) messages respectively, before sending any data packet. This way we can assign the data channel time slots to more sensor nodes than the available resources, which the system would block otherwise.

6.4.1 Enhanced System Performance Using Proposed DTSS Model

Consider the case of an increased number of connection-request arrivals where the number of total requested slots is more than that of the available radio resource (slots). In the proposed model, we accept more connections. If we accept M connections and each connection may transmit q slots per frame, then all M connections may occupy Mq slots. If a maximum of n ($n < Mq$) slots are available at a given CH, the radio resource is not enough to serve immediately and the packets are dropped. Therefore, Equation (6.6) which provides the number of slots occupied by multislot-occupied sensor nodes without packet dropping, needs some modification. The modified distribution with less radio resource yields

$$P'(k) = \sum_{m=\lceil k/q \rceil}^M P(k | m)P(m) \quad \text{where } 0 \leq k \leq n \quad (6.12)$$

where $\sum_{k=0}^n P'(k) = 1$. Therefore, we need normalization to define $P'(k)$. Thus,

$$P'(k) = \frac{1}{X} \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m = 0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.13)$$

where, X is the normalization factor and can be written as

$$X = \sum_{k=0}^n \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m = 0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.14)$$

Thus the enhanced channel utilization with the proposed system is

$$E_2 = \frac{1}{n} \sum_{k=0}^n k p'(k) \quad (6.15)$$

We can accept more connections using the proposed DTSS system model. If one CH has 30 slots per frame and each connection may have maximum 3 slots, then by using the DTSS model we can accept more than 10 connections. The enhanced channel utilization using the proposed system model is depicted in Figures 6.5 and 6.6. The comparison between Figure 6.2 and Figure 6.5 for $a=0.2$ and between Figure 6.3 and Figure 6.6 for $a=0.5$ shows clearly that the proposed system model can provide high channel utilization.

Figure 6.7 shows the reduced connection blocking probability with the proposed system. Comparison of Figure 6.4 and Figure 6.7 shows clearly that the proposed system model lowers the connection blocking probability and enables the provision of more connections to the requesting sensor nodes.

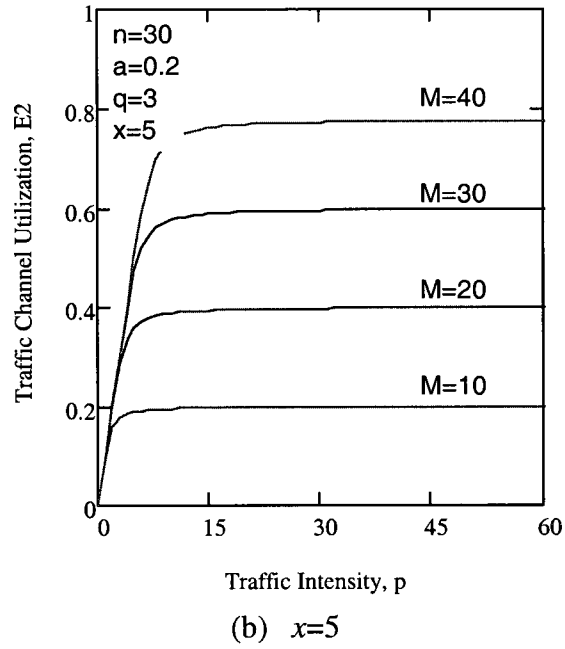
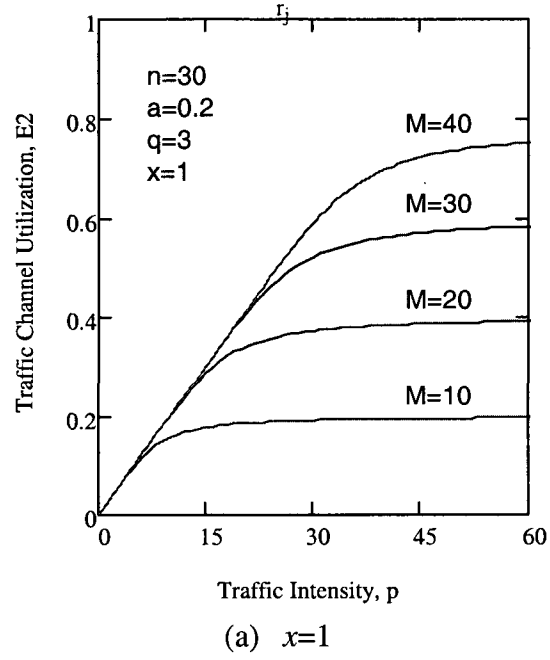


Figure 6.5: Traffic channel utilization using DTSS model with $a = 0.2$

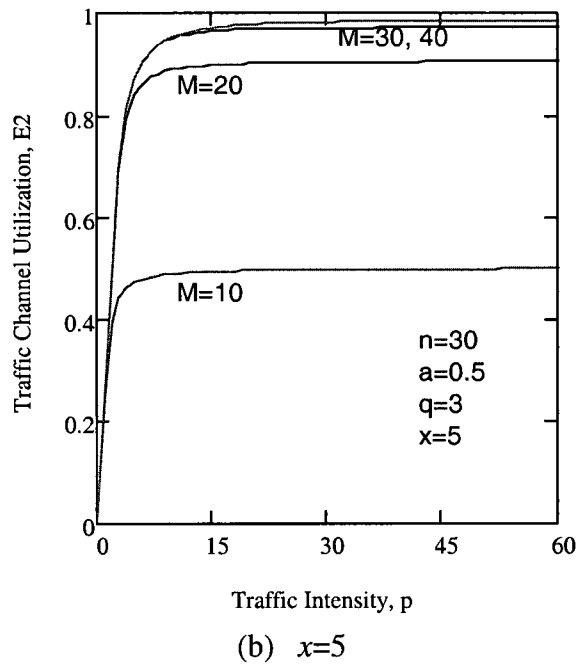
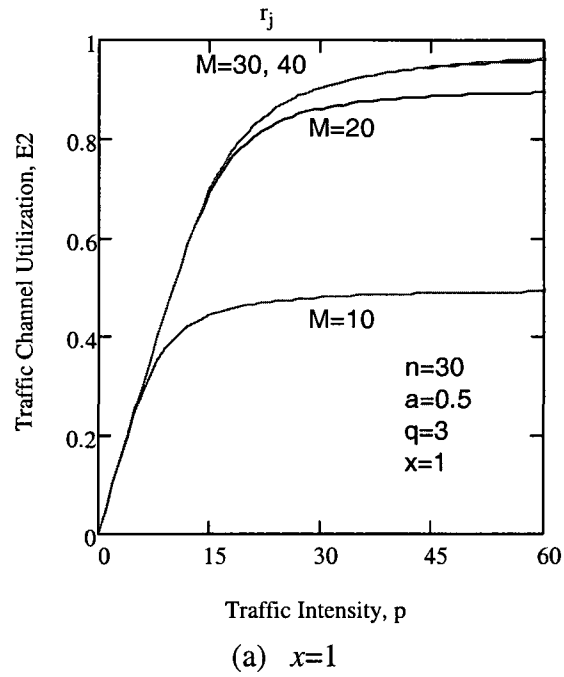
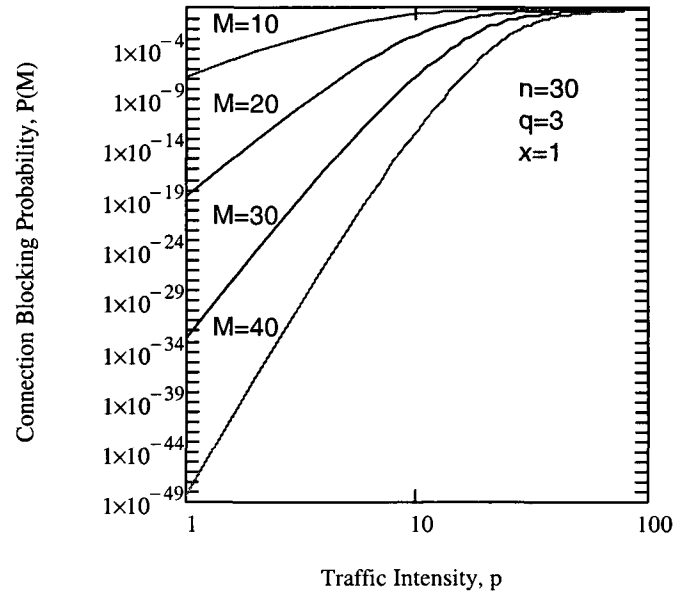
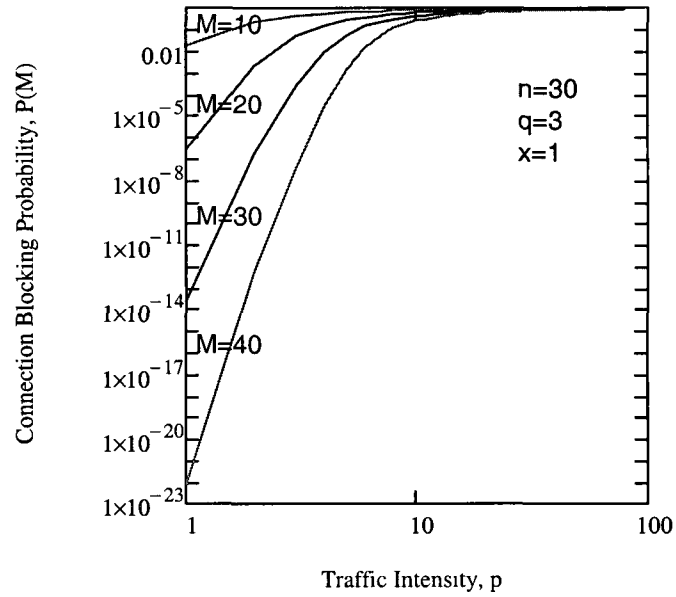


Figure 6.6: Traffic channel utilization using DTSS model with $a = 0.5$



(a) $x=1$



(b) $x=5$

Figure 6.7: Connection blocking probability using DTSS model

6.4.2 Performance Drawback of the Proposed DTSS Model

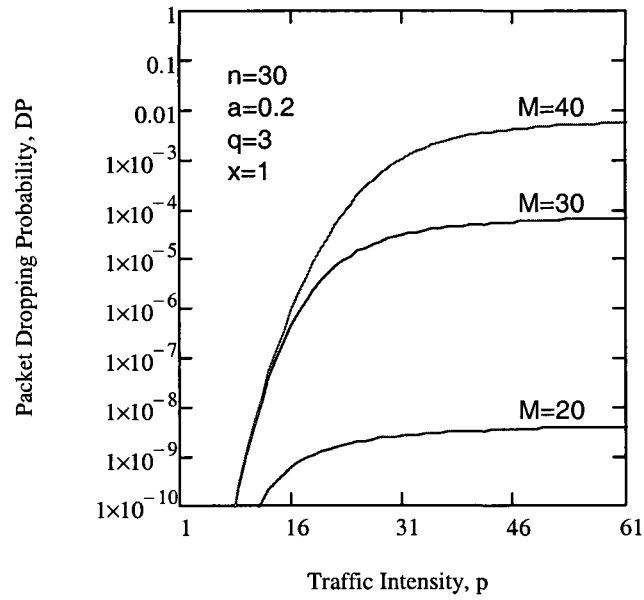
In the DTSS model, we allow more connections to use the unused slots. If the number of packets generated is more than the available slots, then the surplus packets are dropped. The average number of dropped packets per frame is

$$D = \sum_{k=n}^{Mq} (k-n) \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m=0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.16)$$

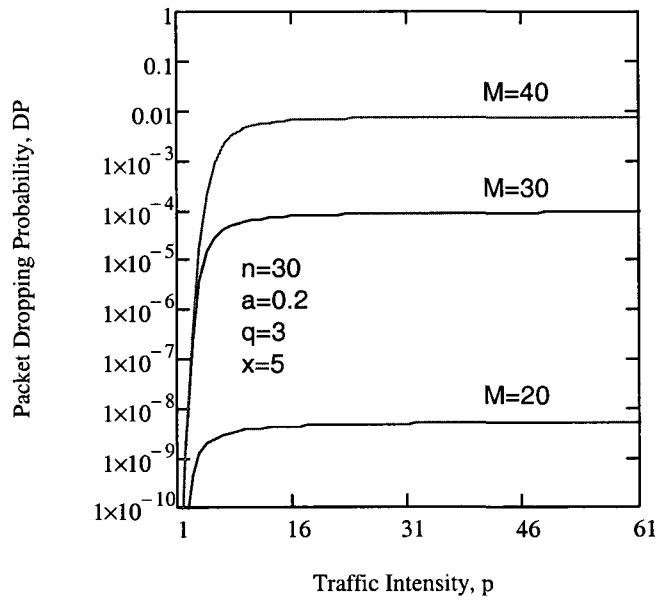
The average number of total packet arrivals per time frame is shown in Equation (6.10). The packet dropping probability is the ratio of dropped packets to the arriving packets. So, the packet dropping probability in the DTSS model is given by

$$DP = \frac{D}{A} = \frac{1}{A} \sum_{k=n}^{Mq} (k-n) \sum_{m=\lceil k/q \rceil}^M \left\{ \begin{array}{ll} \frac{1}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{if } m=0 \\ \frac{\frac{1}{x} \cdot \frac{(\rho x)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(\rho x)^k}{k!}} & \text{else} \end{array} \right\} \binom{mq}{k} a^k (1-a)^{mq-k} \quad (6.17)$$

The numerical result of Equation (6.17) is depicted in Figures 6.8 and 6.9 for two different values of activity factor. With $x=1$ and $a=0.2$, the packet dropping probability is zero for the number of connections less than or equal to 10. Here the packet dropping is applied only if more than 10 connections are connected. With $x=5$ and $a=0.5$, the packet dropping probability goes very high. With same activity factor but lower correlation, the packet dropping probability stays within 10 percent for 16 or lower traffic intensity. Focusing on Figure 6.8, it reflects that a careful treatment of accepted connection can provide very low packet dropping probability. It demonstrates that the proposed model can provide enhanced performance with an acceptable level of packet dropping probability.



(a) $x=1$



(b) $x=5$

Figure 6.8: Packet dropping probability using DTSS model with $a = 0.2$

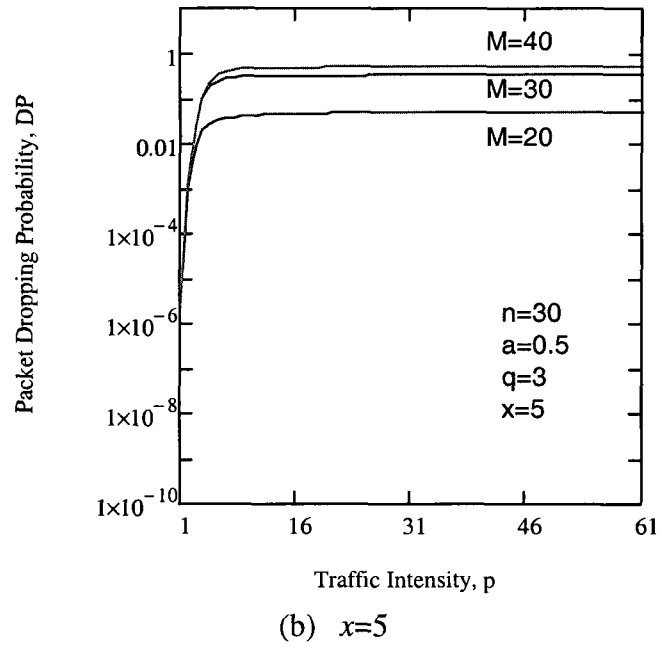
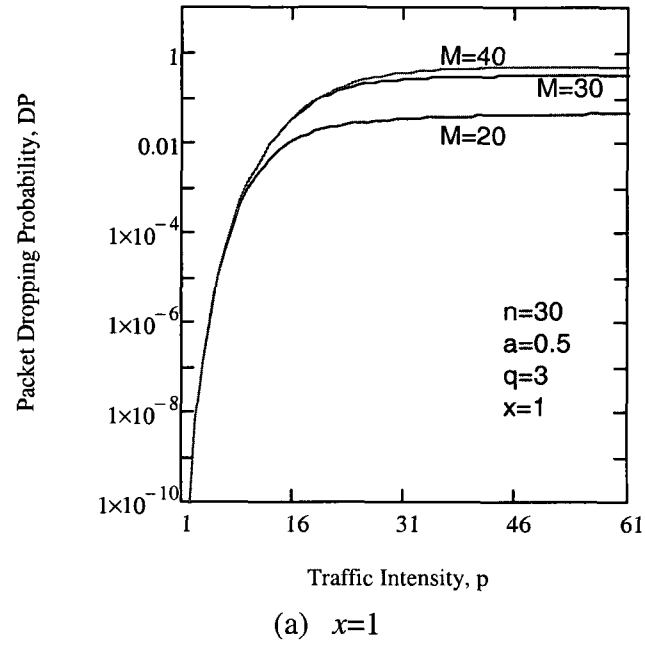


Figure 6.9: Packet dropping probability using DTSS model with $a = 0.5$

6.5 ***Summary***

In this chapter, we have presented the DTSS model, an adaptive and dynamic TDMA slot scheduling model on top of our DSA scheme, where time slots are assigned to the sensor nodes on the fly, according to the need. The main goal of this study is to reduce the wastage in channel bandwidth, especially in low activity networks and varying data traffic. From the proposed analytical model of DTSS, we have obtained the enhanced channel efficiency and the lower connection blocking probability. The drawback of the proposed model is that if more packets are generated in a frame than the number of slots in a frame, then those packets are dropped. The packet dropping probability is also evaluated. We have validated the proposed model by numerical analysis and have proved the improvement in channel utilization and connection blocking probability.

Chapter 7

Conclusion and Future Research

7.1 *Concluding Remarks*

The cluster reliability and energy-efficiency of Wireless Sensor Networks (WSN) affect the performance of other protocols such as routing protocols, signalling protocols or transport layer protocols. This thesis has provided the cluster longevity by extending the cluster lifetime with the introduction of Backup Cluster-Head node (BCH) in those clusters where not a single sensor node can execute the task of Cluster-Head node (CH) completely for a full round. The eligibility of a BCH is validated in the beginning of every round. If the energy of the selected CH, which is assumed the best sensor node in its cluster in terms of energy, is not enough to complete the round, then a BCH is assigned as a backup to that CH. The BCH acts like a normal sensor node until a threshold time indicated by a watchdog timer, which is calculated according to the residual energy of CH. Once the timer fires, the BCH starts to send SOS signals piggybacked with its data packets and waits for SOS response. The CH after receiving the SOS signal checks its own energy and decides if it can continue for another frame. If it cannot continue, it sends the SOS response to the BCH with all the accumulated data and transfers the cluster-head responsibility to the BCH. This provides the maximum coverage of the network and reduces the data loss sensed and sent by the sensor nodes.

We have then modeled the cluster reliability of BCH-based clustered WSN, using Markov chain model. We have used a non-homogeneous Markov process and have adopted the Forward Chapman-Kolmogorov equations to compute the cluster states in a

finite three state space model. The presented model has been tested to match the behaviour of the cluster state transition that we have observed in the simulation. The proposed Markov chain based model can be applied to any three-state fault-tolerance system with varying transition probabilities and a given initial state probability vector.

This thesis has also provided a Dynamic Slot Assignment (DSA) TDMA scheme to achieve the energy efficiency in the cluster-based WSN for low activity networks with varying data traffic. The DSA MAC scheme is an adaptive and dynamic TDMA slot scheduling model, where time slots are assigned to the sensor nodes on the fly, according to the need of the sensor nodes. The DSA scheme reduces the energy loss in the data transmission phase and minimizes the wastage in the channel bandwidth. The DSA scheme requires all the sensor nodes to have dual channel or dual band transceivers. One channel is used for control signalling and the other channel for data traffic. When any sensor node has data to send, it communicates with its CH and sends a connection-request on signalling channel. The CH in return establishes the connection with the requesting node and assigns a time slot in the TDMA frame in the data channel. Once the gathered data are transmitted, the connection with the CH is dropped. In this way, the DSA preserves the channel efficiency of the network, and allows the sensor nodes to join or leave the network dynamically.

We have presented the system model and the analytical model of the DSA scheme. The data traffic has been modeled by a correlated stochastic process (i.e. Markov chain) for a network where the second and subsequent connection arrival rate is dependent on the first arrival rate. We have numerically compared our DSA model with a traditionally proposed static TDMA model, the BMA model, and a variant of the BMA model (EA-TDMA), and proved substantial improvement in the energy consumption and channel utilization in low activity sensor networks. The results have showed that the energy efficiency and channel efficiency of the MAC protocol can be increased significantly using the presented model in the low activity networks.

The DSA MAC scheme performance is high as long as the network activity is low. But when the network activity increases causing high data traffic, the DSA scheme starts blocking the requests of the sensor nodes. To cope with this situation we have proposed

Dynamic TDMA Slot Scheduling (DTSS) on top of the DSA model. It adds two features in the DSA MAC scheme with the likelihood of packet dropping. First, it lets the sensor nodes to have more than one slot in a frame up to a defined maximum limit, so if they have a burst of data at any time then they can send them as quickly as possible. Second, it allows slot-stealing which enables the system to reuse the unused slots which are already assigned to the sensor nodes and temporarily re-assigns them to the new requesting sensor nodes. We have compared the DTSS model with plain DSA model and have proved a significant improvement in the bandwidth efficiency, and have showed a decrease in connection blocking probability. We have also investigated the limitation of the proposed system and modeled the packet dropping probability. The results have showed that the efficiency of the DSA MAC protocol can be increased significantly using the proposed model with reasonably low packet dropping probability.

7.2 ***Future Research***

In the following lines, we present the open issues and the future research direction that should be undertaken in any future work:

Interaction of BCH based network with other layer protocols: The BCH analysis provided in this thesis is based on a simplified model of the network layer and the interaction with the other layers such as MAC and transport layers is not taken deeply into account. The presence of the BCH may have some impacts on these layers in one way or another, the development of a detailed analytical model should be done that encompasses this interaction.

Mathematical model of cluster reliability with dual BCH in clustered WSN: We have presented the analytical model for a three-state Markov chain of a single BCH-based cluster network. Employing dual BCH in a cluster makes a little complex four-state Markov chain model. The solution to this model once derived can be used in any four-state fault-tolerance system with varying transition probabilities and a given initial state probability vector.

Extension of the DSA model for high activity networks: The DSA scheme presented in this thesis performs better for low activity networks. A similar MAC layer model

should be designed that may cater for high activity networks. Hence, the two MAC layer schemes combined together, can be a highly energy-efficient and bandwidth efficient MAC protocol for WSN for every traffic condition of network with a modest blocking probability and little dropping probability.

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Appendix A

Derivation of Average Number of Sensor Nodes in Every Frame

In every frame, the sensor nodes in the cluster send the request packets to the CH at the rate of λ per frame and after getting the connection or the time slot in the data channel they stay connected for $1/\mu$ frames at an average. So from Equation (5.16), using the probability of m sensor nodes being connected in a cluster, we can find the average number of sensor nodes connected out of M possible connections in every frame:

$$m_{ave} = \sum_{m=1}^M mP(m) \quad (A.1)$$

$$\Rightarrow m_{ave} = \sum_{m=1}^M m \frac{\frac{1}{x} \frac{(x\rho)^m}{m!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \quad (A.2)$$

$$\Rightarrow m_{ave} = \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \sum_{m=1}^M m \frac{(x\rho)^m}{m!} \quad (A.3)$$

$$\Rightarrow m_{ave} = \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \sum_{m=1}^M \frac{x\rho(x\rho)^{m-1}}{(m-1)!} \quad (A.4)$$

$$\Rightarrow m_{ave} = \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} x\rho \sum_{m=1}^M \frac{(x\rho)^{m-1}}{(m-1)!} \quad (\text{A.5})$$

$$\Rightarrow m_{ave} = \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} x\rho \sum_{m=0}^{M-1} \frac{(x\rho)^m}{(m)!} \quad (\text{A.6})$$

$$\Rightarrow m_{ave} = x\rho \sum_{m=0}^{M-1} \frac{(x\rho)^m}{(m)!} \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \quad (\text{A.7})$$

$$\Rightarrow m_{ave} = x\rho \sum_{m=0}^{M-1} \frac{(x\rho)^m}{(m)!} \frac{\frac{1}{x}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \quad (\text{A.8})$$

Suppose

$$X = \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!} \quad (\text{A.9})$$

Then m_{ave} will become

$$\Rightarrow m_{ave} = x\rho \left[\frac{\frac{1}{x}}{1+X} + \frac{\frac{1}{x} \frac{(x\rho)}{(1)!}}{1+X} + \frac{\frac{1}{x} \frac{(x\rho)^2}{(2)!}}{1+X} + \dots + \frac{\frac{1}{x} \frac{(x\rho)^{M-1}}{(M-1)!}}{1+X} \right] \quad (\text{A.10})$$

$$\Rightarrow m_{ave} = x\rho \left[\frac{\frac{1}{x}}{1+X} + \frac{1}{1+X} + \frac{\frac{1}{x} \frac{(x\rho)}{(1)!}}{1+X} + \frac{\frac{1}{x} \frac{(x\rho)^2}{(2)!}}{1+X} + \dots + \frac{\frac{1}{x} \frac{(x\rho)^{M-1}}{(M-1)!}}{1+X} \right. \\ \left. + \frac{\frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1+X} - \frac{1}{1+X} - \frac{\frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1+X} \right] \quad (\text{A.11})$$

$$\Rightarrow m_{ave} = x\rho \left[\frac{\frac{1}{x}}{1+X} + 1 - \frac{1}{1+X} - \frac{\frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1+X} \right] \quad (\text{A.12})$$

$$\Rightarrow m_{ave} = x\rho \left[1 - \frac{1 - \frac{1}{x} + \frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1+X} \right] \quad (\text{A.13})$$

Putting the value of X back in (A.13)

$$\Rightarrow m_{ave} = x\rho \left[1 - \frac{1 - \frac{1}{x} + \frac{1}{x} \frac{(x\rho)^M}{(M)!}}{1 + \sum_{k=1}^M \frac{1}{x} \cdot \frac{(x\rho)^k}{k!}} \right] \quad (\text{A.14})$$

Appendix B

Confidence Intervals

Simulated quantities such as *Data Loss Ratio (DLR)* are measured by taking the mean of a succession of n runs, each of long enough time to ensure uncorrelated results. All runs are identical and independent from each other. The n independent results will be represented by $DLR_1, DLR_2, DLR_3, \dots, DLR_{n-1}, DLR_n$, where DLR_i is the average *Data Loss Ratio* obtained from the simulation run i .

$$\text{The mean } \overline{DLR} = \frac{1}{n} \sum_{i=1}^n DLR_i \quad (\text{B.1})$$

However, the mean of the independent simulation runs $\overline{DLR}$ provide us with a single numerical value for the estimate of the expected value of $E[DLR] = \eta$. In order to know how good the estimate is, provided by $\overline{DLR}$ for the simulation results, it is necessary to compute the variance V^2 .

$$\text{The Variance } V^2 = \frac{1}{n-1} \sum_{i=1}^n (DLR_i - \overline{DLR})^2 \quad (\text{B.2})$$

Small V^2 indicates that the results are tightly clustered around $\overline{DLR}$ and we can be confident that $\overline{DLR}$ is close to the $E[DLR]$. On the other hand, if V^2 is large, the results are widely dispersed about $\overline{DLR}$ and we cannot be confident that $\overline{DLR}$ is close to the $E[DLR]$. Instead of seeking a single value to estimate the $E[DLR]$, we can specify an interval of values that is highly likely to contain the true value of the parameter. We begin by specifying some high probability, say $1-\beta$, we then find an interval $[L(DLR), U(DLR)]$ such that:

$$\text{The Probability } P [L (DLR) \leq \eta \leq U (DLR)] = 1 - \beta \quad (\text{B.3})$$

This interval contains the true value of the parameter with probability $1-\beta$, such an interval is $(1-\beta) \times 100\%$ confidence interval.

Using the standard deviation and the t distribution table, the lower and upper limits of the 95% confidence interval can be calculated as follows:

$$\text{Lower Limit } U(DLR) = \overline{DLR} - \frac{1}{\sqrt{2}} \sigma t_{[\frac{\beta}{2}; n-1]} \quad (\text{B.4})$$

$$\text{Upper Limit } U(DLR) = \overline{DLR} + \frac{1}{\sqrt{2}} \sigma t_{[\frac{\beta}{2}; n-1]} \quad (\text{B.5})$$

where

$$\beta = 0.05$$

$$n = \text{number of observations}$$

$$\overline{DLR} = \text{sample average}$$

$$\sigma = \text{sample standard deviation} = \sqrt{V^2} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (DLR_i - \overline{DLR})^2}$$

The confidence interval means that 95% of the simulation results fall within the interval. The confidence interval for the simulation results obtained in Chapter 3 of this thesis is computed based on eight independent runs. From the table of the t distribution, given in Table B.2, the $t_{[\frac{\beta}{2}, 7]}$ is found to be 2.365. It has been observed that more than 95% of the results were within the calculated confidence interval for each experiment. Table B.1 shows an example of how the confidence interval is calculated. The table shows the *Data Loss Ratio* performance of the seven cluster sensor network without the Backup Cluster-Head option enabled, illustrated in Chapter 3, Figure 3.11. The *Data Loss Ratio* for eight independent runs are shown together with the calculated mean $\overline{DLR}$, the upper and lower values of the interval $U(DLR) - L(DLR)$. The confidence intervals are visible for a few results in the figures, since the intervals were relatively small as illustrated in the example below.

Table B.1: Example of Confidence Interval Calculation

Time	Simulation Runs for DLR								$\overline{DLR}$	σ	$L(DLR)$	$U(DLR)$
	DLR_1	DLR_2	DLR_3	DLR_4	DLR_5	DLR_6	DLR_7	DLR_8				
20	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0
220	0	0	0	0	0	0	0	0	0	0	0	0
240	0	0	0	0	0	0	0	0	0	0	0	0
260	0.003767	0.003767	0.004288	0.004288	0.003767	0.003767	0.003767	0.003767	0.003897	0.000241	0.003695	0.004099
280	0.010594	0.010782	0.011267	0.011106	0.010486	0.010594	0.009902	0.010782	0.010689	0.000415	0.010342	0.011036
300	0.042829	0.043207	0.044261	0.043783	0.041238	0.040834	0.038883	0.043197	0.042279	0.001809	0.040767	0.043791
320	0.072351	0.076477	0.078076	0.077753	0.076719	0.07468	0.071581	0.077906	0.075693	0.002552	0.073559	0.077827
340	0.104987	0.110623	0.110467	0.109366	0.108984	0.106441	0.104684	0.110188	0.108218	0.00247	0.106152	0.110283
360	0.135281	0.141116	0.141701	0.140287	0.139149	0.13813	0.13533	0.141053	0.139006	0.002556	0.136869	0.141143
380	0.16567	0.170185	0.169809	0.168798	0.164362	0.167431	0.159401	0.169367	0.166878	0.003653	0.163824	0.169932
400	0.186777	0.194226	0.193047	0.183321	0.186162	0.194003	0.183973	0.195386	0.189612	0.005029	0.185407	0.193817
420	0.200866	0.206186	0.207868	0.199448	0.197221	0.205791	0.201158	0.204498	0.20288	0.003737	0.199755	0.206004
428.1	0.202836	0.206411	0.208399	0.200106	0.197985	0.205532	0.203149	0.204446	0.203608	0.003379	0.200783	0.206433

Table B.2: *t*-Distribution Critical Values

One	75%	80%	85%	90%	95%	97.50%	99%	99.50%	99.75%	99.90%	99.95%
Two	50%	60%	70%	80%	90%	95%	98%	99%	99.50%	99.80%	99.90%
1	1	1.376	1.963	3.078	6.314	12.71	31.82	63.66	127.3	318.3	636.6
2	0.816	1.061	1.386	1.886	2.92	4.303	6.965	9.925	14.09	22.33	31.6
3	0.765	0.978	1.25	1.638	2.353	3.182	4.541	5.841	7.453	10.21	12.92
4	0.741	0.941	1.19	1.533	2.132	2.776	3.747	4.604	5.598	7.173	8.61
5	0.727	0.92	1.156	1.476	2.015	2.571	3.365	4.032	4.773	5.893	6.869
6	0.718	0.906	1.134	1.44	1.943	2.447	3.143	3.707	4.317	5.208	5.959
7	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.029	4.785	5.408
8	0.706	0.889	1.108	1.397	1.86	2.306	2.896	3.355	3.833	4.501	5.041
9	0.703	0.883	1.1	1.383	1.833	2.262	2.821	3.25	3.69	4.297	4.781
10	0.7	0.879	1.093	1.372	1.812	2.228	2.764	3.169	3.581	4.144	4.587
11	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	3.497	4.025	4.437
12	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.428	3.93	4.318
13	0.694	0.87	1.079	1.35	1.771	2.16	2.65	3.012	3.372	3.852	4.221
14	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.326	3.787	4.14
15	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.286	3.733	4.073
16	0.69	0.865	1.071	1.337	1.746	2.12	2.583	2.921	3.252	3.686	4.015
17	0.689	0.863	1.069	1.333	1.74	2.11	2.567	2.898	3.222	3.646	3.965
18	0.688	0.862	1.067	1.33	1.734	2.101	2.552	2.878	3.197	3.61	3.922
19	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.174	3.579	3.883
20	0.687	0.86	1.064	1.325	1.725	2.086	2.528	2.845	3.153	3.552	3.85
21	0.686	0.859	1.063	1.323	1.721	2.08	2.518	2.831	3.135	3.527	3.819
22	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.119	3.505	3.792
23	0.685	0.858	1.06	1.319	1.714	2.069	2.5	2.807	3.104	3.485	3.767
24	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.091	3.467	3.745
25	0.684	0.856	1.058	1.316	1.708	2.06	2.485	2.787	3.078	3.45	3.725
26	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.067	3.435	3.707
27	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.057	3.421	3.69
28	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.047	3.408	3.674
29	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.038	3.396	3.659
30	0.683	0.854	1.055	1.31	1.697	2.042	2.457	2.75	3.03	3.385	3.646
40	0.681	0.851	1.05	1.303	1.684	2.021	2.423	2.704	2.971	3.307	3.551
50	0.679	0.849	1.047	1.299	1.676	2.009	2.403	2.678	2.937	3.261	3.496
60	0.679	0.848	1.045	1.296	1.671	2	2.39	2.66	2.915	3.232	3.46
80	0.678	0.846	1.043	1.292	1.664	1.99	2.374	2.639	2.887	3.195	3.416
100	0.677	0.845	1.042	1.29	1.66	1.984	2.364	2.626	2.871	3.174	3.39
120	0.677	0.845	1.041	1.289	1.658	1.98	2.358	2.617	2.86	3.16	3.373
∞	0.674	0.842	1.036	1.282	1.645	1.96	2.326	2.576	2.807	3.09	3.291