

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**A NEW ENERGY EFFICIENT
FORWARDER SET BASED DYNAMIC DUTY CYCLED ROUTING
IN WIRELESS SENSOR NETWORKS**

M.Sc. THESIS

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Department of Computer Engineering

Computer Engineering Programme

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**KABLOSUZ SENSÖR AĞLARINDA
YÖNLENDİRME KÜMESİNE GÖRE DİNAMİK GÖREV ÇEVİRİMLİ
YENİ BİR YÖNLENDİRME TEKNİĞİ**

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Babama,

FOREWORD

Since last year of bachelor of science, I have worked on wireless sensor networks. I have deep knowledge on WSN during this period. I would express my gratitude to my supervisor, Prof. Dr. Sema OKTUĞ and her valuable insights directions during the thesis.

I appreciate my mother, my father, my sister and my little niece for their faith in me and for the inspiration.

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ABBREVIATIONS

| | |
|-------------|-------------------------------|
| WSN | : Wireless Sensor Networks |
| MAC | : Medium Access Layer |
| RTS | : Request to send |
| CTS | : Clear to send |
| SYNC | : Synchronization |
| ACK | : Acknowledgement |
| ETX | : Expected Transmission Count |
| EAX | : Expected Any Path Count |
| EDC | : Expected Duty Count |
| E2E | : End to End |
| GPS | : Global Positioning System |
| TTL | : Time to Live |

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A NEW ENERGY EFFICIENT FORWARDER SET BASED DYNAMIC DUTY CYCLED ROUTING IN WIRELESS SENSOR NETWORKS

SUMMARY

Wireless sensor networks (WSN) consists of energy-constrained, tiny sensor nodes that collect data (temperature, pressure, humidity etc.) from environment. Sensor nodes have low computational capabilities and constrained energy. So energy efficiency of sensor nodes becomes critical for WSNs. Idle listening causes unnecessary energy consumption for nodes. Sensor nodes consume energy in idle listening as much as in packet receiving. Duty cycling is widely applied for preventing idle listening.

Forwarder set based dynamic duty cycling method is proposed. In proposed model, nodes update their duty cycle in a distributed manner. There are no communication overhead and energy consumption due to coordination among sensor nodes. XMAC in MAC layer and contention-based geographic forwarding in network layer are adopted in the thesis. In XMAC, sender sends short preambles to next hop. If one of the preambles is detected by the intended receiver, the node sends back an ACK. If the detecting node is not the intended next hop, the node goes back to sleep. In contention-based geographic forwarding, the nodes in the forwarder set a timer, when the node receives one of the preambles. The closest node to the sink has the smallest timer. So the timer of the closest nodes expires first. Then the closest node sends back an ACK and the other nodes in the forwarder set return back their duty cycle. Finally data transmission between sender and receiver begins. XMAC is modified for supplying compatibility between XMAC and contention-based geographic forwarding. Therefore, preambles contain the geographic location of sender node.

Each sensor node knows the times that it has been in the forwarder set and the times that it has been next hop in packet transmission. If sensor node has been in forwarder set but it is not selected as next hop frequently, then it decreases its duty cycle for increasing the probability of being next hop. Vice versa, if sensor node has been next hop so frequently, it implies that the node has been the next hop at many packet transmissions. Then duty cycle of the node is reduced to decrease the energy consumption of node. Furthermore remaining energy of the nodes is used as a constraint in proposed duty cycle adjustment model.

Proposed duty cycle adjustment scheme obtains two times longer lifetime comparing with node degree based duty cycling scheme and six times longer lifetime comparing with constant duty cycling. Remaining energy of nodes distributed evenly in WSN comparing with node degree based dynamic duty cycling and constant duty cycling. Alternatively, delay performance degraded slightly comparing with constant duty cycling.

Secondly, adaptive sink selection scheme is applied to nodes that works with forwarder set based dynamic duty cycling for failure resistance. Multi-sink WSNs are adopted in the scheme. Sender nodes tries to send its packet to a potential receiver. If any node

in forwarder set does not send ACK after maximum allowable sleeping time, sender node *feels* node failure. Then, the sender node complements its forwarder set. It can forward the packets through the nodes that are farther to the sink than itself. Packets can be forwarded to other sink by this way. If sender node can not send its packet to a neighbour node after determined number of preambles, the node sends its packet any of its neighbours by complementing its forwarder set.

In the evaluations for adaptive sink selection scheme, WSN with four sink is adopted. Proposed model is tested with four node failure scenario. Each sink creates its virtual regions that consists of the nodes whose closest sink is itself. In the proposed scheme, it works same as regular geographic forwarding in no failure case. Packet loss rate is dropped and throughput is increased comparing with geographic forwarding in node failure scenarios. Furthermore, delay performance is slightly decreased comparing with geographic forwarding. It is an expected results. When re-routing the packet to other sinks, the number of hops that packets are forwarded, is increased. Here, degradation in delay is tolerable compared with reduced packet loss rates.

To sum up, we have studied dynamic duty cycle assignment problem and introduced a distributed scheme based on remaining energy and forwarder set of nodes. Secondly, we have studied fault tolerance in multi-sink WSNs and introduced an adaptive geographic forwarding technique in order to prevent packet loss due to node failures. Number of preambles is employed to estimate node failures. In this thesis, we aim to develop a self-organized WSN. Nodes decide their duty cycles and their forwarder set themselves. Coordination causes communication overhead and energy consumption due to packet transmissions. There is no need to coordination amongst sensor nodes for duty cycle adjustment and failure detection.

In the future work, we are planning to improve the performance of the next hop nodes by working on preambles. The forwarder set based duty cycle scheme introduced will be studied extensively by simulations under heavy traffic with ultra low duty cycled nodes paying attention to collisions. Furthermore we are planning to fine tune the detection of node failures by varying the number of preambles, N_{max} , and using some other parameters obtained from the sensor nodes.

KABLOSUZ SENSÖR AĞLARINDA YÖNLENDİRME KÜMESİNE GÖRE DİNAMİK GÖREV ÇEVİRİMLİ YENİ BİR YÖNLENDİRME TEKNİĞİ

ÖZET

Kablosuz sensör ağları günümüzde yaygın olarak kullanılmaktadır. Kablosuz sensör ağlarında, bir ortama rastgele veya düzenli olarak yerleştirilmiş yüzlerce düğüm sıcaklık, nem, basınç vb. çevresel etmenlerin ölçümünü yaparak bir veya birden fazla merkez düğüme iletir. Sensör düğümlerin işlemci kapasitesi düşüktür ve enerji kısıtlamaları vardır. Sensör düğümlerin enerji kısıtı kablosuz sensör ağlarında enerji veriminin önemini arttırmıştır.

Sensör düğümler paket iletimi yapmadıkları sırada dinleme durumunda bulunurlar. Sensör düğümler, paket iletimi yapmadıkları ancak çevreyi dinledikleri zamanlarda gereksiz bir enerji tüketiminde bulunurlar. Bu dinleme durumuna *boş dinleme (idle listening)* denir. *Boş dinlemenin* sebep olduğu enerji tüketimini azaltmak için görev çevrimli çalışma sıkça kullanılan bir yöntemdir. Görev çevriminde sensör düğümler uyku ve dinleme zamanlarından oluşan bir periyodu takip etmektedirler. Düğümler uyku zamanlarında herhangi bir paket alışverişi yapmamakta ve enerji tüketimlerini olabilecek minimum seviyeye düşürmektedirler. Dinleme zamanlarında ise paket alışverişi yapabilmektedirler.

Görev çevrimi(duty cycling) periyodu bütün düğümler için belirli ve ağıın yaşam süresi boyunca sabit olabilir. Sabit görev çevrimli (static duty cycling) sensör düğümler, ağıın dinamiklerine uyum sağlayamaz ve düğümler ağıdaki konum ve görevlerine göre görev çevrimlerini güncelleyemez. Diğer yandan görev çevrimi periyodunu dinamik olarak güncellenen düğümler ağıın yaşamı süresince değişen şartlarına daha kolay uyum sağlar. Bu sebeple bu tez kapsamında dinamik görev çevrimli(dynamic duty cycling) sensör düğümler üzerinde bir çalışma yapılmıştır.

Dinamik görev çevrimli sensör düğümlerde akla gelen en önemli soru görev çevriminin sensör düğümler nasıl güncelleneceğidir. Sensör düğüm görev çevrimini başka sensör düğümler veya merkez düğüm(sink) ile haberleşerek güncelleyebilir. Bu yöntem, düğümler arasında paket aktarımı gerektirdiğinden ağı içinde haberleşme yüküne (communication overhead) dolayısı ile enerji tüketimine sebep olur. Bu sebeple bu çalışmada sensör düğümlerin paket aktarımına gerek duymadan görev çevrimlerini güncelleyeceği yöntem geliştirilmiştir.

Yönlendirme kümesine göre dinamik görev çevriminde (forwarder set based dynamic duty cycling), sensör düğümler paket iletimleri sonucunda elde ettikleri verileri kullanarak bazı istatistikler elde ederler. Bu istatistiki verileri kullanan sensör düğümler, görev çevrimlerini günceller. Geliştirilen yöntemde düğümün kalan enerji miktarı bir kısıt olarak belirlenmiştir. Dinamik görev çevrimi yönteminde düğümler, görev çevrimlerini güncellerken başka düğümler ile paket alışverişine gerek duymamıştır.

Görev çevrimi, Ortam Erişim Katmanı(MAC Layer) ile alakalı bir konudur. Ortam Erişim Katmanında görev çevrimini içeren birçok protokol literatürde bulunmaktadır. Dinamik görev çevrimli yöntem gerçekleşmeden önce Ortam Erişim Katmanında çalışmamıza uygun bir protokol olan XMAC gerçekleştirilmiştir. XMAC protokolünde, gönderici düğüm kısa süreli paketler göndererek, uygun olan komşularına haber verir. Komşu düğümlerden uyku durumunda olmayan veya o sırada paket iletimi yapmayan alıcı düğüm, bir geri bildirim paketi(ACK) gönderir. Daha sonra gönderici düğüm ve alıcı düğüm arasında paket iletimi başlar.

Fırsatçı yönlendirme(opportunistic routing) protokolleri görev çevrimli kablosuz sensör ağlarda sıkça kullanılır. Kaynak ve varış arasında belirlenmiş sabit bir yol üzerinden paket iletimi yapan yönlendirme protokollerinde, yol üzerindeki alıcı düğümün uyanması için uzun süre beklenilebilir veya bu düğüm enerjisinin tükenmesi vb. sebebiyle paket iletimi yapmıyor olabilir. Paketin potansiyel bütün alıcı düğümler yardımı ile, statik yollar belirlenmeden aktarılması, gecikme ve iş çıkarımı performansı konusunda daha iyi sonuçlar alınmasını sağlar. Bu çalışmada ağ katmanında, düğümlerin coğrafi konumlarına göre fırsatçı yönlendirme yapan çekişme temelli coğrafi yönlendirme(contention-based geographic forwarding) protokolü gerçekleştirilmiştir.

Çekişme temelli coğrafi yönlendirme protokolünde alıcı düğümler, göndericiden gelen kısa paketlerden(preamble) birini aldığı anda merkez düğüme olan uzaklıklarına göre bir zamanlayıcı kurar. Merkez düğüme en yakın olan düğümün zamanlayıcısı en erken sürede sona erer. Zamanlayıcısının süresi dolduktan sonra merkez düğüme en yakın olan düğüm gönderici düğüme bir geri bildirim paketi gönderir. Bu geri bildirim paketini alan gönderici düğüm paket iletimine başlar, zamanlayıcısı dolmayan diğer düğümler de görev çevrimlerine geri döner. XMAC protokolü ve çekişme temelli coğrafi yönlendirme protokolü arasında uyumluluğu sağlamak için göndericinin gönderdiği kısa paketlere, gönderici düğümün konum bilgisi de eklenmiştir.

Kablosuz sensör ağındaki her düğüm, gönderici düğümün yönlendirme kümesinde(forwarder set) bulunup bulunmadığı ve alıcı düğüm olup olmadığı konusunda bilgi sahibidir. Sensör düğümler kaç kere yönlendirme kümesinde bulunduğu bilgisi ve kaç kere alıcı düğüm olma çekişmesini kazandığı bilgisine sahiptir. Bu çalışmada sensör düğümlerin paket aktarımları sırasında elde ettikleri bu veriyi kullanarak görev çevrimlerini güncellemesi sağlanmıştır. Bir sensör düğüm yönlendirme kümesinde çok kez bulunuyor ancak alıcı düğüm olarak seçilmiyorsa bu düğüm görev çevrimindeki uyanıklık süresini artırarak alıcı düğüm olma ihtimalini artırır. Tam tersi olarak, eğer bir düğüm yönlendirme kümesinde bulunma sayısının büyük bir kısmında alıcı düğüm oluyor ise bu düğüm uyanıklık süresini azaltarak hem uyanıklık süresinde harcadığı enerji miktarını azaltır hem de alıcı düğüm olarak seçilme olasılığı azalır.

Bunun dışında, kalan enerji miktarı da görev çevrimi güncellemesinde kısıtlayıcı olarak kullanılmıştır. Eğer bir düğümün kalan enerji miktarı azalmışsa görev çevriminde uyanıklık süresi arttırılacaksa bile daha küçük bir oranda arttırılır. Bu sayede, bu düğümün kalan enerjisini de tüketip, kısa sürede ölmesi engellenir.

Yönlendirme kümesine dayalı görev çevrimi yöntemi ile ağın yaşam süresi, sabit görev çevrimine göre altı kat, düğüm derecesine dayalı dinamik görev çevrimi(node degree based duty cycling) yöntemine göre ise iki kat arttırıldı. Ağın yaşam süresi dolduktan sonra, düğümlerin kalan enerji miktarları diğer yöntemlere göre daha dengeli bir

dağılım gösterdi. Diğer yandan, gecikme konusunda da sabit görev çevrimine göre tolere edilebilir bir artış gözlemlendi.

Bu tezde geliştirilen bir diğer yöntem ise sensör düğümlerin düğüm bozulmalarına karşı duruma dayalı merkez düğüm seçimidir(adaptive sink selection). Düğüm bozulmalarına karşı dayanıklı kablosuz sensör ağlar günümüzde gittikçe önem kazanmaktadır. Bu amaçla ağa birden fazla merkez düğüm yerleştirilmektedir. Düğüm bozulmaları sonucunda paketlerin düşmesi ağda istenmeyen bir durumdur. Ayrıca, düğüm bozulmaları sonucu ağda oluşan boşluklar(routing hole) sık görülmektedir. Geliştirilen yöntem ile düğümler bozulduğu veya düğümlere erişilemediği zaman paketler, coğrafi olarak başka yönlere ve başka merkez düğümlere yönlendirilmiştir.

Geliştirilen yöntemde gönderici düğüm paket göndereceğine dair kısa paketler yayınlamaya başlar. Eğer kısa paketleri gönderme süresi ağdaki izin verilen maksimum uyuma süresinde fazlaysa ve herhangi bir düğümden geri bildirim alamıyorsa, gönderici düğüm yönlendirme kümesinin tümleyenini alır. Kısacası yönlendirme kümesine farklı düğümler dahil edilir. Bu durumda gönderici düğüm elindeki paketi, merkez düğüme kendisinden daha uzak olan düğümlere de iletebilir. Paketler diğer merkez düğümlerin olduğu bölgelere doğru yönlendirilmiş olur.

Coğrafi yönlendirme protokollerinde, düğüm bozulması durumunda, gönderici düğüm paketi coğrafi kazanım ile gönderebileceği bir alıcı düğüm bulamayabilir. Bu durumda paketler gönderici düğümler tarafından iletilemez ve gönderici düğüm sürekli kısa bildirim paketleri göndererek enerjisini tüketir. Gönderici düğümün diğer merkez düğümlere doğru paketleri yönlendirmesi gereklidir. Önerilen yöntemde gönderici düğümler yeterli süre bekledikten sonra, paketi iletemediklerine karar verip yönlendirme kümesini tümlemektedirler. Bu sayede paketlerin düşme oranı azalmakta ve iş çıkarımı artmaktadır.

Duruma göre merkez düğüm seçimi yöntemi, çeşitli düğüm bozulması senaryoları ile test edilmiştir. Bu senaryolarda düğümlerin bozulması sonucu ağda boşluklar oluşturulmuştur. Düğüm bozulmaları içeren senaryolarda, geliştirdiğimiz yöntem paketlerin başka merkez düğümlere yönlendirilmesini sağlamıştır. Yapılan simülasyonlar sonucunda, coğrafi yönlendirmeye(geographic forwarding) göre paket düşme oranları azalmış ve iş çıkarımında artış görülmüştür. Gecikme performansında coğrafi yönlendirmeye göre bir düşüş gözlemlenmiştir. Bu beklenen bir sonuçtur. Çünkü paketler diğer merkez düğümlere yönlendirildiğinde kaynak ve varış arasındaki yol uzamaktadır. Gecikmedeki artış, iş çıkarımında elde edilen artış ile karşılaştırıldığında tolere edilebilecek seviyededir.

Sensör düğümlerin dağıtık bir şekilde karar alarak görev çevrimini güncellediği ve duruma göre merkez düğüm seçimi yaptıkları bir sistem tasarlanmıştır. Tasarlanılan sistemde ortam erişim katmanında XMAC protokolü, ağ katmanında ise çekişme temelli coğrafi yönlendirme protokolü kullanılmıştır. Simülasyon sonuçları olay tabanlı kablosuz bir ağın gerçekleşmesi ile elde edilmiştir. Bu sebeple her düğümün kaynak(source) olabileceği ve bütün paketlerin bir merkez düğüme ulaşmak istedikleri var sayılmıştır. Ağ trafiği belleksiz özelliği ile gerçekleştirilebilir olan poisson dağılımına göre yaratılmıştır. Ağın yaşam süresi(network lifetime) ağın bölünmesi(network partition) olarak belirlenmiştir.

Sonuç olarak, geliştirilen yöntemde fazladan haberleşme yükü ve gereksiz enerji tüketimi engellenmeye çalışılmıştır. Sensör düğümler, ağ hakkında global bir bilgiye

sahip olmadan yerel düzeyde ađın dinamiklerine uyum sađlamıřtır. Bu da geliřtirilen yöntemlerin büyük boyutlu kablosuz sensör ađlara da uyumlu olmasını sađlamıřtır.

1. INTRODUCTION

Wireless sensor networks (WSN) consists of energy-constrained, tiny sensor nodes that collect data (temperature, pressure, humidity etc.) from environment. Wireless sensor networks has attracted great interest over the last decade. Low-cost, low power and multifunctional small sensor nodes have become available through the recent developments in electronics and wireless communications [5].

1.1 Problem Definition

Energy efficiency is highly related with network lifetime. So reducing energy consumption is critical for lifetime of sensor nodes. Energy consumption is highly depended on radio subsystem. Sensor nodes send or receive packet for the purpose of both packet transmission to destination and coordination among themselves. If coordination among sensor nodes is is required in the WSN, the solution could not be scalable. Furthermore, coordination among sensor nodes causes highly communication overhead and energy consumption.

1.2 Purpose of Thesis

We aim to design self-organizing WSN for lessening energy consumption, prolonging network lifetime and obtaining failure resistance. In our proposed model, nodes adjust their duty cycles and forwarder set by their own. Sensor nodes do not need to communicate with their neighbours or sink node for determining their duty cycles or forwarder set. So energy consumption due to coordination among sensor nodes and communication overhead are reduced significantly. Therefore, our proposed model is robust to large-scale WSNs and mobile sensor nodes.

1.3 Author Contribution

Our contributions can be listed as below,

- Duty cycling in sensor nodes are employed for preventing idle listening.
- Energy balance among the sensor nodes is aimed. Because critical nodes (highly used nodes in packet transmissions) deplete their energy after a short period of time. Then packet loss rate increases. We try to balance energy consumption for prolonging the network lifetime.
- We used dynamic duty cycling for balancing energy consumption. If energy consumption rate of any node is high, then node decreases its duty cycle for energy conservation.
- Nodes update their duty cycle based on statistics obtained from network layer and remaining energy of nodes.
- Nodes only have a metric that is defined for network density in deployment phase and no other global knowledge.
- Nodes also update their potential receiver nodes in the case of routing holes and node failures. Packets forwarded through alternative paths with slightly increasing delay for preventing packet loss.
- Nodes update their duty cycle and forwarder set in self-organizing manner. Therefore, there is no communication overhead that is caused by coordination among nodes.
- Finally, single sink model and multi-sink model are considered in our evaluations.

1.4 Structure of The Document

This thesis is organized as follows: literature survey that includes asynchronous MAC layer protocols, opportunistic routing protocols and duty cycling methods , are given in the next chapter. Chapter 3 presents the proposed model for dynamic duty cycling and adaptive sink selection by complementing the forwarder set. Simulation results of

various metrics, such as network lifetime, delay, throughput and so on, are shown in Chapter 4. Finally Chapter 5 concludes the thesis by giving future directions.

2. LITERATURE SURVEY

In the proposed model, we develop a WSN using an asynchronous MAC protocol in the MAC layer and geographic forwarding in the network layer. We adopted dynamic duty cycling. We proposed forwarder set based dynamic duty cycling for obtaining energy fairness among the sensor nodes. Furthermore an extension to geographic forwarding is suggested for failure resistance in multi-sink WSNs. Finally we considered both single sink WSNs and multi-sink WSNs in the evaluations.

So theoretical background can be divided into four parts: MAC layer protocols, opportunistic routing protocols, dynamic duty cycling schemes and multi-sink WSNs.

2.1 Duty Cycled Wireless Sensor Networks

There is idle time that sensor nodes do not do any packet transmissions or sense the environment. The idea behind the duty cycling is preventing idle listening of each sensor node. So duty cycling is widely applied method for preventing idle listening and unnecessary energy consumption in WSNs. Duty cycle gives the fraction of active periods in the lifetime of a node. Node lifetime has a cyclic structure changing from listen to sleep then listen again and so on. In listen periods, nodes can send or receive packets. Nodes can not do any packet transmission in sleep periods and they turn into the energy saving mode.

Duty cycling supplies energy efficiency especially in WSNs that needs to operate more than a few days before recharging the battery [6]. Sensor nodes consume most of their energy at packet transmission. So duty cycling is widely adopted method for WSNs because of energy efficiency.

Periodic schedule of a sensor node can be represented as in Fig.2.1. Duty cycling that is a function of MAC Layer, is employed for energy efficiency on the radio subsystem.

2.2 Mac Protocols for Duty-cycled Wireless Sensor Networks

Duty cycling is a function related with MAC Layer. The radio subsystem is the main reason of energy consumption. So radio subsystem is tried to be turned off for preventing idle listening. So many MAC protocols that support duty cycling for WSNs, are proposed in the literature [7]. MAC protocols with duty cycling can be divided into two groups:

- Synchronous MAC Protocols
- Asynchronous MAC Protocols

2.2.1 Synchronous MAC protocols

In synchronous MAC protocols, nodes have synchronization among them. They send and receive synchronization packets for achieving synchronization. Packet transmissions for synchronization cause energy consumption. However synchronized sensor nodes do not need to wait the wake-up time of the neighboring nodes. So per hop delay performance can not extend the delay threshold.

In [8], a new sensor mac protocol is proposed. Nodes exchange schedules by broadcast. So neighbouring nodes are scheduled together. SYNC packets that only contain address of sender node and its next sleep time. Multiple neighbours can contend for a medium. So request to send (RTS) and clear to send (CTS) messages are used for interfering nodes. Nodes can receive both SYNC packets and data packets in their listen periods. So listen periods are divided into two parts. The first one is for receiving SYNC and the second part is for RTS packets.

SMAC uses fixed sleep and fixed listen periods. The fixed schedules is not optimal for variable traffic load over the WSN. In [1], variable listen period is proposed depend on message rate. Latency requirements and buffer size are generally fixed in WSN. But message rate is generally varied. So they maintained an optimal active time under variable traffic load. They also used SYNC, RTS and CTS packets for synchronization and packet transmission as in [8]. The difference between SMAC and TMAC can be seen in Fig. 2.2.

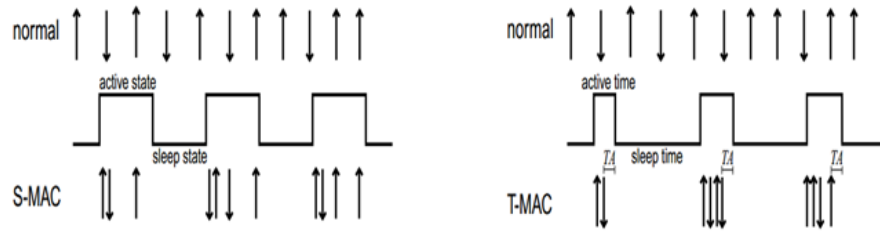


Figure 2.1: SMAC and TMAC visual representation [1].

2.2.2 Asynchronous MAC protocols

There is no communication overhead due to synchronization in asynchronous MAC protocols. So energy-saving is the most favourable side of asynchronous MAC protocols. Asynchronous MAC protocols are robust to large-scale WSNs and supply instant recovery after channel disruption.

In [9], sender sends preambles that contain its address, intended receiver address until the receiver receives one of the preambles. Preamble length is defined as size of sleep interval. Because sender wants to make sure that the receiver is listening for the packet. Long preambles which is sent by sender node, generally cause high energy consumption of the sender node.

An access point learn and keeps the sampling schedules of all sensor nodes. Sampling schedules are obtained by using every acknowledgement packet. By sampling schedule of the destination, sender node can send preambles with minimized duration [10].

In [4], XMAC which is a sender initiated MAC protocol, sender sends short preambles to next hop. If preamble is detected by the receiver (the next node), the node sends back an ACK. If the detecting node is not the intended next hop, it goes back to sleep. Strobed preamble allows receiver not to wait too long until the end of preamble.

A receiver initiated MAC protocol is proposed for depending on rendezvous time between sender and receiver [2]. When sender wants to send a packet, it only remains active. If receiver is ready for receiving a packet, it sends a beacon for informing the sender for packet transmission. RI-MAC increases channel utilization, throughput, packet delivery ratio by its receiver-initiated manner. Visual representation of RI-MAC can be seen in Fig. 2.3.

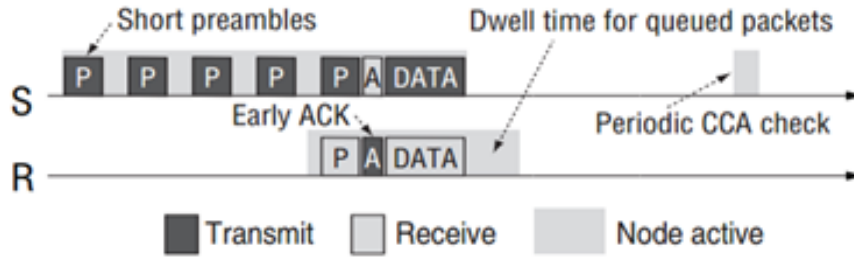


Figure 2.2: RI-MAC visual representation [2].

2.3 Opportunistic Routing Protocols

It is logical to employ opportunistic routing protocols in duty-cycled WSNs instead of optimized fixed routes. Opportunism is used to take the advantage of the active nodes in other directions that could receive packets at packet sending time. The idea behind the opportunistic routing protocols is using the broadcast nature of packet transmission. In opportunistic routing, a forwarder set is determined and the nodes in forwarder set is prioritized based on determined metrics. These metrics can be expected transmission count, hop counts, geometric distance or so on. [11]

Opportunistic routing protocols can be divided into two groups based on the metric of forwarder set prioritization:

- Expected Transmission Count or Hop Count Based Opportunistic Routing Protocols
- Geographic Forwarding

2.3.1 Expected transmission count or hop count based opportunistic routing protocols

Prioritization among the nodes in forwarder set is done based on hop count or expected transmission count. In [12], the source selects forwarder set and prioritizes neighbour nodes by expected transmission count (ETX) value. The node which has smaller ETX value to destination becomes the next hop for the packet transmission. Expected any path count (EAX) is used for forwarder set prioritization [13]. It recursively calculates the near-optimal forwarder set.

Duplicate packet problem arises with the ETX metric. Nodes can be connected with low-quality links or no link. So nodes can make inconsistent decisions on packet forwarding. Some nodes in the forwarder set can not hear ACK packets that send by the selected next hop. Then the nodes that is not selected as the next hop, also send the packet. For solving duplicate transmission, data packets are always coded and carry a list of forwarders. When a node receives a packet, it checks innovativeness of the packet. [14].

In [15], the forwarder set selection criteria is:

$$C_u(Fwd*) = C_u^h(Fwd*) + C_u^f(Fwd*) + C_u^c(Fwd*) \quad (2.1)$$

$C_u^h(Fwd*)$ is the expected cost for a sender to transmit a packet to at least one receiver in the forwarder set. $C_u^f(Fwd*)$ is the expected cost that there is one node in the forwarder set to relay the packet to final destination. $C_u^c(Fwd*)$ is the communication cost for choosing a relay node.

As stated in [16, 17], expected duty count (EDC) metric is used for the forwarder set selection. In EDC metric, delay that is made by the expected number of duty-cycled wake-ups is considered. EDC is formulated as follows:

$$E(DC(i)) = E(DC_s(i)) + E(DC_m(i)) \quad (2.2)$$

$E(DC_s(i))$ is the expected number of duty-cycled wake ups until the packet has been received by one of the forwarders. $E(DC_m(i))$ is the expected number of remaining duty-cycled wake ups to completing multi hop transmission.

The energy optimal tree is created for preventing redundant transmissions and long flooding delay [18]. The expected packet delay is used for the prioritization metric. Packets are grouped as early packets and late packets. Early packets are forwarded to reduce the delay. Late packets are not forwarded to reduce the energy cost.

As mentioned in [19], Poisson distributed wake-up rate is adopted. When sender holds a packet, firstly sender transmits beacons at regular intervals. When any receiving node sends back ACK, sender chooses the ACK transmitter with the best expected

end-to-end (E2E) delay as the next hop forwarder. Sink updates wake-up rate based on the maximum delivery delay.

2.3.2 Geographic forwarding

In geographic forwarding, nodes are assumed to know their exact locations with the help of GPS or localization algorithms. Nodes that are closer to the sink than the sender node, become potential forwarders. The closest node to the sink becomes the next hop. So there are many potential forwarder nodes in the forwarder set, then the closest one to the sink is selected as the next hop.

In [20], each node determines a wake-up slot. Sender node knows the wake-up time of the nodes in the forwarding set. Sender forwards the packet to the active candidate that is the closest one to the sink.

Geographic Random Forwarding (GERAF) is a widely applied geographic forwarding method. The sender sends RTS packets to the nodes in the forwarding set. Furthermore the forwarding set is divided into priority regions. Candidates in the forwarding set competes for becoming the next hop. Firstly only the nodes in the first region (R1) can respond to RTS packets of the sender node. So the nodes in the R1 competes for becoming the next hop. High priority node in R1 sends back CTS packet. If there is no CTS that is sent from the nodes in R1, then sender transmits RTS packets to the second region (R2). GERAF works as sending RTS packets to different prioritized regions in each iteration [3]. Forwarding regions in GERAF can be seen in Fig. 2.4.

In [21], nodes in the forwarding set, determine a timer based on their distance to the sink. The closer node to sink has a timer with smaller value. When the timer of a node expires, the node broadcasts an ACK packet and the other nodes in the forwarding set receive ACK and cancel their timers. Furthermore, a suppression scheme is adopted for determining the region of forwarder set.

As stated in [22], in order to prioritize the nodes based on their distance from destination, each node initializes a timer. Timers are defined based on their distance to the destination.

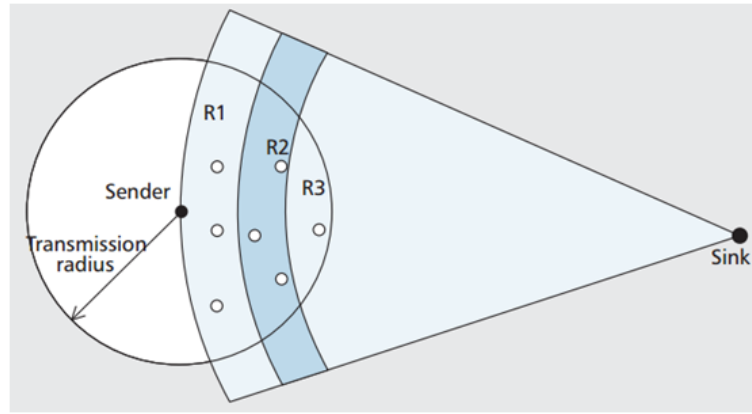


Figure 2.3: GeraF - prioritized forwarding regions [3].

Geographic forwarding is applied to duty-cycled WSN. Because delay performance increases due to packet transmissions with potential forwarders. There are many related works that are about geographic forwarding on duty-cycled WSNs [23].

Geographic forwarding is adopted in duty-cycled WSNs. They suggest a model that at least k awake neighbours are active for packet transmission. Nodes sleep or awake according to the need of k -awake neighbour. By k -awake neighbour, network can be connected during the lifetime of the network [24].

In [25], the forwarder set consists of nodes that are closer to the destination than the sender node. A markov decision is made with minimizing delay and maximizing location progress in each hop. A threshold function between delay and location progress is defined. Sender node sends its packet to the closest awake neighbour or waits for another potential forwarder in the sleeping state. Periodic and un-slotted scheduling adopted in [26]. Forwarding region is determined according to the distance from the sink. However, nodes compete to send CTS depending on their expected E2E delay or remaining energy.

There are some works that use both geographic progress and other metrics for the determining next hop in the forwarder set. In [27], frame delivery ratio and remaining energy are taken into account for determining the next hop. Packet advancement towards destination according to a delivery ratio and remaining energy, are considered. Also an energy harvesting model is adopted in this work.

As stated in [28], three models are suggested. Each node blacklists the potential forwarder nodes that are closer to the destination and reception rate below a certain

threshold, in relative reception based blacklisting. The node with the highest reception rate amongst nodes closer to destination, becomes the next hop in the best reception neighbour model. Lastly, Each node blacklists nodes whose reception rate are under a certain threshold, in absolute reception based blacklisting.

Fuzzy logic system is adopted for selecting the next hop in packet transmissions. Distance of a node to destination can be *near*, *moderate* or *far*. Remaining energy of the node and degree of mobility can be *low*, *moderate* or *high*. Then they create a fuzzy logic system to determine the next hop. [29].

In [30], listen and sleep states of a node are modeled as a Markov chain. The tradeoff between staying active and geographic progress is used in Markov chains. The next hop is determined based on the tradeoff between geographic progress and cost of staying active.

2.4 Dynamic Duty Cycling

Duty cycle adjustment can be divided into two groups. The first one is to update the duty cycle based on the information obtained from the sensor nodes. Traffic rate, distance to sink, packet inter-arrival time, node degree can be obtained by a node and each node decides its duty cycle based on this information. In the second group, nodes communicate with their neighbours for duty cycle adjustment. Moreover, the sink can collect information from sensor nodes and decides their duty cycles in a centralized way. There are high communication overhead and energy consumption in centralized manner. Also centralized manner is not scalable for large-scale WSNs.

In [31], the remaining energy of nodes is taken as a metric to adjust duty cycles. A static threshold and the maximum energy are determined for all nodes. Here, the duty cycle is adjusted by the formula that scales the remaining energy with a threshold value. Moreover, energy harvesting capabilities of the nodes are taken into account.

Another example is Traffic Adaptive Distance Based Duty Cycle Assignment (TDDCA) which adjusts duty cycle with the help of retransmitted RTS messages and the distance to sink [32]. Each node calculates the average traffic rate that is determined by distance to sink. Then the duty cycle is updated by this expected traffic rate and retransmitted RTS messages. High number of retransmitted RTSs means that node's

duty cycle is low and no relay node can be found. In [33], duty cycle is adjusted based on degree of the node. By this heterogeneous and asynchronous duty cycling scheme, they aim to decrease the maximum end-to-end delay in the WSN.

In [34], another adaptive duty cycling method is introduced. Here, nodes send their current listening mode to each other. Nodes update their transmissions depending on the mode of their neighbours. If a node has higher duty cycle, it is penalized with higher routing cost which diverts traffic to other nodes.

A recent work is General Distributed Sleep Interval Control (GDSIC) that formulates the problem as convex optimization. Nodes adjust their duty cycle based on solely local information exchange with their senders and receivers. Their aim is to obtain the optimal sleep interval setting with considering energy efficiency [35].

There are some other works where nodes send their statistics to sink. The sink determines optimized duty cycles for all nodes in a centralized manner. In [36], the sink collects the maximum allowable duty cycle and source traffic rates from nodes. Then it solves the linear programming problem and decides duty cycles of the nodes.

2.5 Multi-sink Wireless Sensor Networks

We also made a literature survey on multi-sink WSNs that are adopted geographic forwarding as their routing protocol, because we adopted geographic forwarding in our work and worked on geographic forwarding on multi-sink WSNs.

In [37], the self organizing controlled potential-based routing (CPBR) is used the number of hops to sink and remaining energy for determining the next hop in multi-sink WSNs. Self-adaptive on demand geographic routing protocol is proposed to find alternative paths in the case of outdated local topology information in mobile ad-hoc networks [38].

In [39], the dynamic destination assignment which is developed for multi-sink WSNs, is achieved by assigning the nearest sink to the sensor nodes. Unfortunately, they neither address the detection of routing holes by the sensor node nor employ duty-cycling in their work.

Furthermore, the distance metric is investigated for geographic forwarding in multi-sink WSNs. So radio coverage based metric has energy gain comparing with euclidean distance [40].

3. AN ENERGY EFFICIENT FORWARDER SET BASED AND DYNAMIC DUTY CYCLE BASED ROUTING APPROACH

The work can be divided into two parts. Nodes work in a self-organizing manner to adapt to the changes in the WSN. They only do packet transmission and they make some estimations that are obtained from their packet transmissions. By the way, they update their duty cycle or their forwarder set in a distributed manner. We aim to decrease the communication overhead that is caused by communicating via neighbours or sink. Moreover nodes can adopt the changes in WSN successfully without the global knowledge of WSN. There is no communication overhead for coordination among the nodes.

Updating the duty cycle based on the statistics of the node has much less overhead. If satisfactory statistics are collected accurately, the network lifetime and the delay can be optimized in WSNs [41]. We introduce a new dynamic duty cycling scheme. In the proposed model, nodes adjust their duty cycle based on the information shared with the network layer and the remaining energy of nodes in a distributed manner. As a result of the evaluations, the network lifetime prolongs and energy balance among sensor nodes is obtained. Moreover the delay performance is not degraded significantly in the proposed dynamic duty cycling model.

Sensor nodes are very sensitive to environmental effects. Failure probability of sensor nodes increases especially in urban areas. Hence failure tolerant WSNs become compulsory for recovery. In WSNs, coordination among the nodes cannot be guaranteed and becomes a complicated task. Self-organizing sensor nodes are robust to network dynamics and have adaptability to node failures, changing traffic conditions and so on.

We present an adaptive geographic forwarding technique considering sink selection in multi-sink dynamic duty-cycled WSNs. Self-organizing sensor nodes try to determine node failures in their neighbours. If the self-organizing sensor node *feels* a failure in its neighbours leading to the sink node, it tries to send its packets by using alternative

nodes opportunistically. So the packet could be rerouted to another sink that has no routing holes. If no failure is *felt*, the proposed technique works as the geographic forwarding technique [42]. Here, after reaching the threshold for per hop delay, sender node begins to suspect from (*feel*) a node failure and complements its forwarding set, which may contain other neighbor nodes different from the nodes in its current forwarder set. By this approach, packets could be forwarded to different sinks that are reachable from the sender node. As a result of extensive simulations using various node failure scenarios, we observed that proposed extension to the geographic forwarding technique drops the packet loss rate effectively. Unfortunately, end-to-end delay increases because the path between source and destination gets longer. There exists a trade-off between delay performance and packet loss [42].

3.1 Energy Efficient Forwarder Set Based Dynamic Duty Cycle Adjustment

We introduced a new dynamic duty cycling scheme. In the method, sensor nodes use the statistics from the network layer and the remaining energy for updating duty cycle. Nodes do not need to communicate with each other before updating their duty cycles. So they get rid of communication overhead. Hence, the network lifetime prolongs and the energy efficiency of the nodes gets better.

Many network lifetime metrics related to network partition time, percentage of dead nodes in topology, threshold for packet delivery rate are defined [43]. Lifetime is generally defined as the time of the first sensor node failure. However, WSNs can be capable of delivering data to sink after the first node failure. So we defined the lifetime as the death time of the node that causes a network partition. Furthermore we take into consideration that delay is another critical metric especially for real-time WSN applications. As a result of extensive simulations using various scenarios we observed that prolonging the network lifetime without degrading the performance of the network significantly by dynamic duty cycle adjustment is the main contribution. In order to make the scheme applicable, the method can be applied to different types of asynchronous MAC protocols and the opportunistic routing protocols [41].

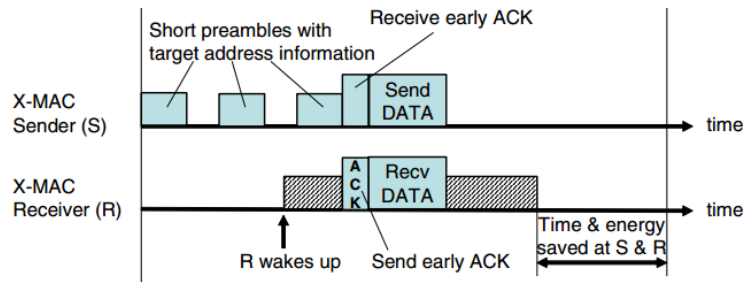


Figure 3.1: The use of short preambles in XMAC [4].

In the rest of this subsection, firstly XMAC protocol is presented. Then a forwarder set based geographic forwarding is introduced. Finally the proposed forwarder set based dynamic duty cycling is given.

3.1.1 XMAC protocol

Each sensor node follows a duty cycle between sleep and active periods. Asynchronous MAC protocols do not need synchronized wake/sleep schedules. So energy-saving is the most favourable side of asynchronous MAC protocols.

In this work, we employed XMAC because of its reduced latency and higher throughput compared with the other MAC protocols [4]. In XMAC which is a sender initiated MAC protocol, sender sends short preambles to the next hop. If a potential receiver is sleeping or sends another packet, it cannot receive the preamble. If a preamble is detected by the receiver (the next node), the node sends back an ACK. If the detecting node is not the intended next hop that is determined by the sender, it goes back to sleep. Strobed preamble allows receiver not to wait too long until the end of preamble as seen in Fig. 3.1.

In XMAC, intended receiver is determined by the sender. However static routes are not appropriate especially in asynchronous duty-cycled WSNs. Sender could wait so long for an intended next hop. Deciding the next hop among the set of potential neighbours as in opportunistic routing protocols, can lead to energy saving. Therefore we modified XMAC for being compatible with opportunistic routing.

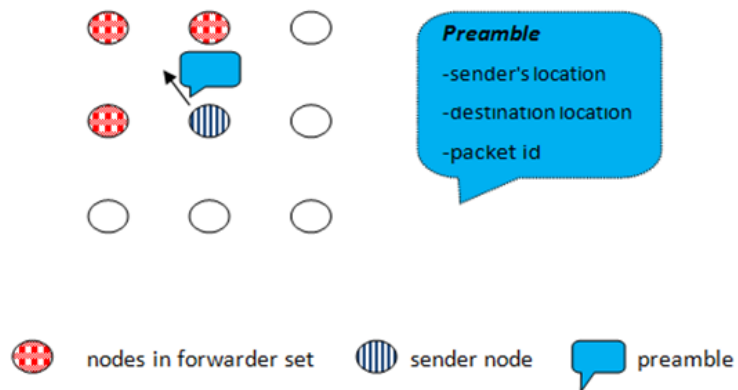
3.1.2 Forwarder set based geographic routing

Opportunistic routing is widely applied routing protocol for duty-cycled WSNs. Opportunism is used to take the advantage of active nodes that could receive packets at packet sending time.

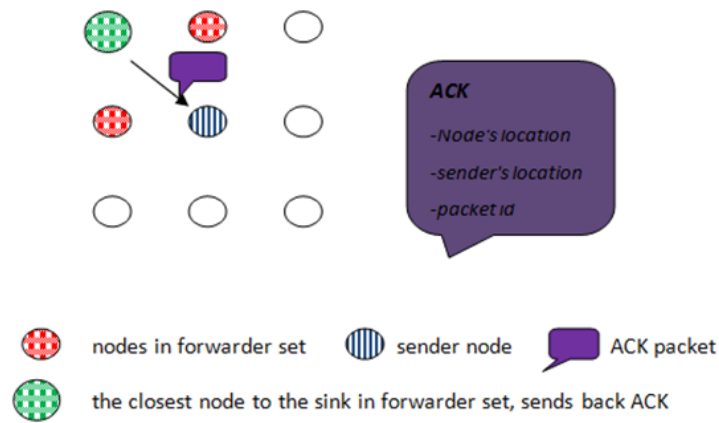
In this work, we employed the contention-based forwarding [21]. In the contention-based forwarding, nodes in the forwarder set, determine a timer based on their distance to sink. The closer node to the sink has a timer with smaller value. When the timer of a node expires, the node broadcasts an ACK packet and the other nodes in the forwarder list receive ACK and cancel their timers. Furthermore suppression schemes are adopted for selecting the node in the forwarder set. The aim of suppression schemes are determining the forwarder set whose nodes are one-hop distance to each other.

It should be noted that each sender tries to send a packet to an intended next hop in XMAC. However, the next hop is not intended and is selected among the potential forwarder nodes in contention-based forwarding. Compatibility between XMAC and contention-based forwarding must be supplied. Sender sends preambles that contain its location, destination location and packet id for compatibility between XMAC and contention-based forwarding [44]. Each neighbor sender, who receives the preamble and is closer to the destination than the sender, sets up a timer and contents to serve as the next hop.

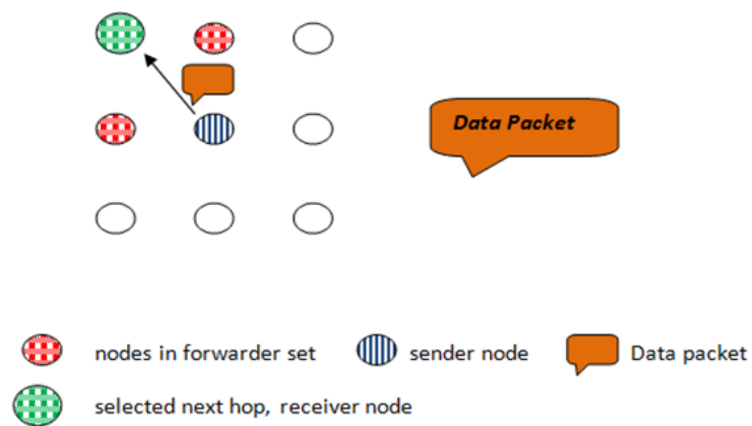
In Fig. 3.2., XMAC and geographic forwarding which are adopted in the evaluations are presented. We supplied compatibility between geographic forwarding and XMAC for duty-cycled WSNs. Firstly sender (blue node) sends preambles. The node which is in the forwarder set and is not sleeping, receives the preamble and sets a timer based on their distance to the sink. If the node is sleeping, it cannot receive the preambles. The nodes in the forwarder set does not need to know the specific location of the destination. Preamble contains the information about the location of the specific destination. The closest node to the sink (green node) sends back an ACK firstly. Because its timer expires firstly. Then the packet transmission begins between the sender and the receiver.



(a) Preamble Sending.



(b) The closest node to the sink sends back ACK.



(c) Packet transmission between sender and receiver.

Figure 3.2: Geographic forwarding and XMAC.

3.1.3 Energy efficient dynamic duty cycling technique introduced

Forwarder set based duty cycling scheme combines the remaining energy of nodes and the information obtained from the network layer. Firstly, the sender node decides on the direction of duty cycle adjustment (whether increment or decrement). The decision is done based on the information obtained from the network layer.

In one-hop packet transmission, more than one nodes are generally included in the forwarder set. One of them is selected as the next hop. Some nodes could not be the next hop in spite of being in the forwarder set. These nodes could be the next hop for balancing energy consumption among nodes.

Nodes collect two statistics which are represented by ε and θ , on each duty cycle adjustment period. Nodes do not keep any additional information like sender or other nodes in the forwarder set. ε gives the number of times that the sensor node has been in the forwarder set at each duty cycle adjustment period. θ is the number of times that the node has been the next hop. Furthermore, it is assumed that the mean number of nodes in a forwarder set for the WSN is known and named as α . α is a variable related with node degree. So it is assumed to be known the density of the network at the deployment phase.

The duty cycle adjustment is done based on the remaining energy of the nodes considering their current duty cycle as given in (1).

$$d_i = \begin{cases} d_i + (c \times d_i \times (\frac{E_R}{E_{full}})) & \theta < (\varepsilon/\alpha) \\ d_i - (c \times d_i \times (1 - \frac{E_R}{E_{full}})) & \theta > (\varepsilon/\alpha) \end{cases} \quad (3.1)$$

where d_i is duty cycle of node i . c is network specific constant which determines the range of the duty cycle update. E_R and E_{full} are remaining energy of the node and initial energy of the node, respectively.

ε/α gives the mean number of times that each node has been next hop. If energy consumption rates of each node in WSN are similar, number of packets that they send should be similar. Energy balance among the nodes can be provided by similar number of packet transmissions among nodes. Because sensor nodes consume most of their energy on packet transmissions. If any node sends too many packets comparing with its neighbours, it can deplete its energy. In basic way, ε/α supplies network-wide

threshold for finding the nodes that send too many packets comparing with their neighbours.

If θ of a node is lower than ε/α , it means that the node does not have the chance of being the next hop frequently. So its duty cycle is increased for increasing the probability of being the next hop. It is assumed that every node has the probability of $1/\alpha$ as being the next hop. If θ of the node is lower than ε/α , it implies that the node has been the next hop at many packet transmissions. Then duty cycle of the node is decreased to reduce the energy consumption of node. Such an approach decreases the probability of being active on the next packet transmissions for the node.

Remaining energy is used as a constraint in duty cycle adjustment. If the remaining energy of the node reduces dramatically, duty cycle of the node is not increased with a higher rate. We considered energy depletion of the nodes as a constraint. So we used the ratio between the remaining energy of the nodes and the full energy of nodes as a scaling parameter in the heuristic in (3.1). $\frac{E_R}{E_{full}}$ scales duty cycle increment for preventing energy depletion of highly-used nodes. Vice versa, $(1 - \frac{E_R}{E_{full}})$ scales the duty cycle decrement by considering the remaining energy of the nodes. If the remaining energy of the node is high, then its duty cycle decreases with a lower scaling.

Finally, it should be noted that the nodes which are placed especially in the corners of WSNs usually do not have a chance to be the next hop in many packet transmissions. They only generate packets and send the packets to the next hop. Hence, ε can be used to check if the corresponding node is whether a corner node or not. If ε of the node is zero for a long period, duty cycle of the node is decreased dramatically. Because duty cycle of the node is not adjusted and the node does not send or receive packets in many duty cycle adjustment periods. Then the nodes begin to deplete their energy in listening periods. Hence, the nodes consume their energy in idle listening. Thus, duty cycle of these type of nodes can be decreased dramatically for preventing idle listening. On the other hand, the death of these type of nodes does not affect the network lifetime. Therefore, we cannot observe performance gain in the evaluations by extending the lifetime of these type of nodes.

3.2 Adaptive Sink Selection Using Forwarder Set Based Dynamic Duty Cycling

We present an adaptive geographic forwarding technique considering sink selection in multi-sink dynamic duty-cycled WSNs. Firstly self-organizing sensor nodes try to determine node failures in their neighbours. Then it tries to send its packets by using alternative nodes opportunistically, if the self-organizing sensor node detects a routing hole in its forwarder set.

We determined the maximum waiting time for detecting routing hole by a sensor node. Maximum number of preambles is defined for representing maximum waiting time. The sensor node sends its packet to the next hop with the per hop delay in XMAC (3.2) [1].

$$\begin{aligned} L_{at} = & (duration\ of\ preamble + ACK\ listen) \\ & \times (expected\ number\ of\ iterations\ required) \\ & + (duration\ to\ send\ packet) \end{aligned} \quad (3.2)$$

The maximum number of iterations required to send a packet can be obtained with using allowable maximum sleep period in WSN. In the worst case, the node sends preamble and all of its neighbours begin their sleep periods. So any of the neighbours of the sensor node become active and cannot receive packet until the end of sleep period. We defined N_{max} that is maximum number of preambles send by the sensor node as in (3.3).

$$N_{max} = \frac{(T_{sleep} + T_{pre} + T_{ACK})}{(T_{pre} + T_{ACK})} \quad (3.3)$$

where, T_{sleep} is duration of maximum allowable sleep period. T_{pre} is duration of preamble and T_{ACK} is duration of acknowledgement that is sent by the node in the forwarder set.

On the other hand, if the traffic rate is high and any node can be a source in the WSN, the number of preambles can be higher than N_{max} . When the sender node sends preambles, the neighbors of the sender node also could send preambles or receive packets. The maximum number of preambles to send a packet can be greater than

N_{max} , while considering all the possible cases. So the maximum number of preambles needs to be defined higher. But, the aim of duty-cycling is preventing idle listening and generally is applied in WSNs that have not high traffic rates. If traffic rate is high, sleeping time of nodes become to lessen due to packet transmissions and preamble sending. So the cases that the maximum number of preambles is higher than N_{max} , are also so rarely in low duty-cycled WSNs.

In WSNs, nodes can be broken and some of the sink nodes cannot be reachable by the sensor nodes. So the packets that are routed to unreachable sink nodes, are dropped and throughput performance decreases. We modified contention-based forwarding in order to direct these packets to one of the other sinks in multi-sink WSNs and reduce packet loss rate. We proposed an extension for obtaining failure resistance in multi-sink WSNs.

In the model, the sender node suspects from *feels* a node failure after sending N_{max} preambles. N_{max} preambles is a threshold for estimating node failure or routing hole. After reaching the threshold, sender node attempts to complement its forwarder set and notify the extension of its forwarder set to its neighbours by its preambles.

We also modified contention-based forwarding by extending forwarder set in the case of node failure. In contention-based geographic forwarding, if the closest node to sink sends back an ACK, all the other nodes in forwarding region can hear the ACK and return back to their duty cycles. So all the nodes in the forwarder set are one-hop distance to each other. In the proposed model, forwarder set is complemented after sending N_{max} preambles. So all the nodes in the forwarder set may not be one-hop distance to each other. We add a *receiver node* field in data packets of the sender node. The modification in contention-based forwarding can be summarized step by step:

- Sender node sends preambles to nodes in its forwarder set.
- The timer of the closest node to the sink expires firstly. The closest node to the sink sends back an ACK.
- Sender node waits the end of the waiting time for all ACKs that are send by other nodes in the forwarder set.
- Sender node sends data packets whose *receiver node* field contains the node with the smallest timer.

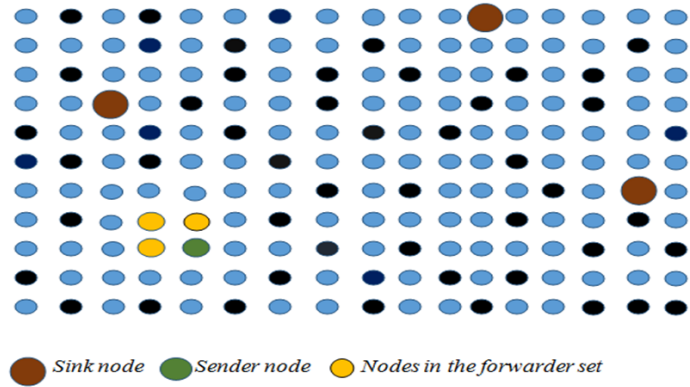
- The nodes in the forwarder set check the data packet whether they are the next hop or not. If they are not the next hop, then they return back their duty cycle period.

Preambles contain the sender node's location, location of the destination sink, *flexible field* and packet id for compatibility between XMAC and contention-based forwarding [44]. *Flexible field* is set as active, if the sender node estimates a node failure. If the sender node cannot send its packet to any next hop after N_{max} preambles, it begins to consider the possibility of failure or the possibility of energy drain. So it sets *flexible field* as active in the preambles.

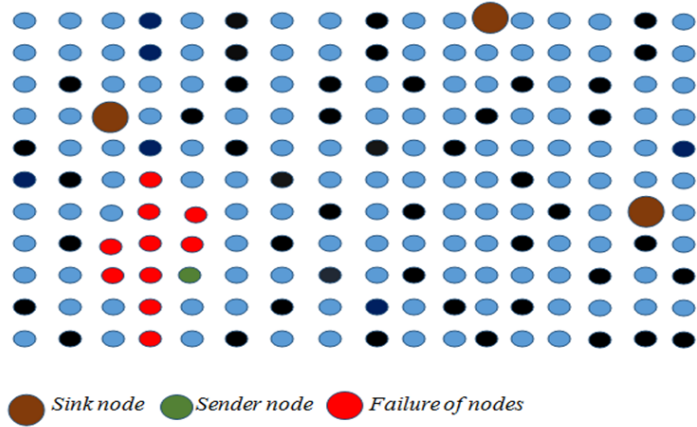
Normally, a neighbour node that receives a preamble, responds an ACK, if and only if it is closer to the destination sink than the sender node. When less than N_{max} preambles are sent, the routing protocol works same as the geographic forwarding. When the sender node sends N_{max} preambles, the sender node sets the *flexible field* as active in its preambles. All of the neighbours that receive such preamble, send an ACK, if they are farther to the destination sink than the sender node. Moreover, the node also complements its forwarder set, if it receives n packets whose flexible fields are active. So packet are not ping-ponged among similar nodes and are forwarded to other sink with less number of hops.

When a source node decides to transmit a packet opportunistically, it sets the network-wide defined *flexible limit* in the packet. *Flexible limit* depends on the network size and the number of sinks in the WSN. If *flexible limit* is not assigned properly, delay performance degrades drastically due to longer paths between source and destination.

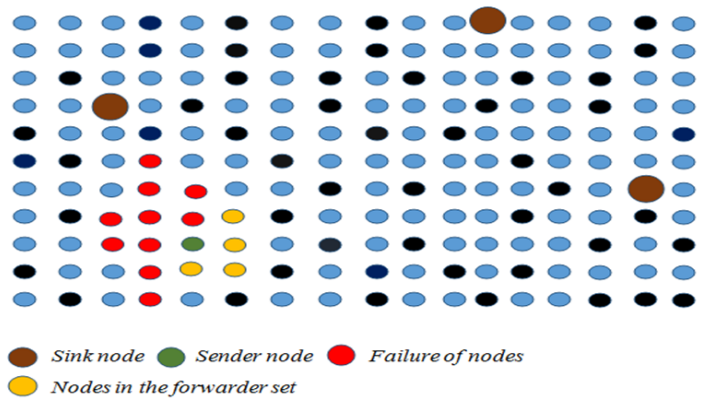
In Fig.3.3 and Fig. 3.4., the proposed approach is demonstrated. Black nodes represent nodes in sleeping period. The sender node (green node) sends its packets to the nodes in its geographic forwarder set (yellow nodes). Some nodes are dropped because of energy depletion or failure (red nodes). So sender node can not transmit its packets to red nodes in its forwarder set. If the sender node cannot transmit its packet to a next hop node after N_{max} preambles, the forwarder set is complemented and the number of alternative receivers is changed. If receiver node receives n packets whose flexible fields are active, it also complements its forwarder set. Packets can use alternative paths. Hence, the packet can reach to other sinks without ping-pong among similar nodes. Packet loss can be decreased by changing the members of the forwarder set.



(a) No Failure Case- Geographic Forwarding to nearest sink.

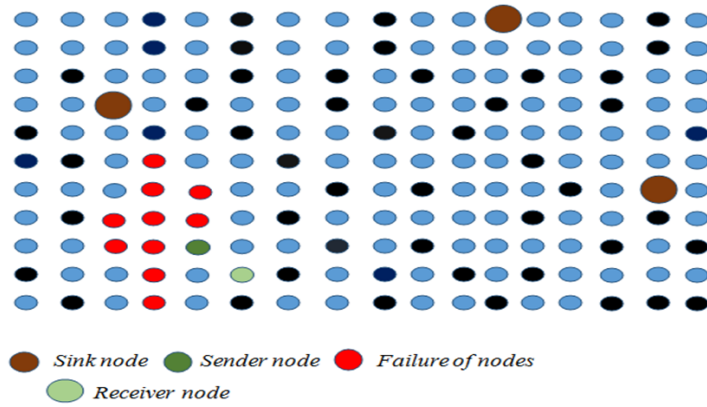


(b) The nodes in forwarder set are failed.

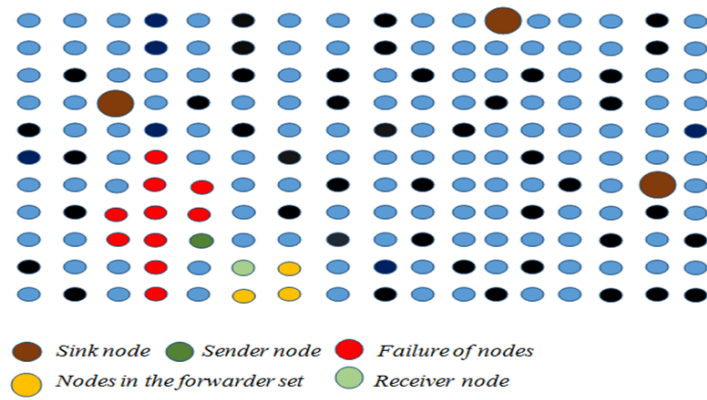


(c) Forwarder set is complemented after detection of node failures.

Figure 3.3: Update of forwarder sets - I.



(a) The receiver node in the new forwarder set.



(b) Forwarder set is complemented after receiving n packets whose flexible fields are active.

Figure 3.4: Update of forwarder sets - II.

4. RESULTS OBTAINED

In the previous sections, we mention the design principles and the properties of the forwarding set based dynamic duty cycling and adaptive sink selection in multi-sink WSNs. In this section, we present the simulation environment and the performance comparison of the proposed techniques with the others.

4.1 Simulation Environment

Simulation results are obtained from discrete event simulation developed using the Java programming language. It is assumed that sensor nodes know their exact location with the help of GPS or localization algorithms. The assumption is made by all the related works which adopt geographic forwarding.

XMAC and contention-based geographic forwarding are employed in the simulations. For XMAC, simulation parameter values are taken similar to those in [4]. Furthermore, energy consumption parameters of sensor nodes, that include computational cost, are set based on TelosB mote specification [45]. Computational cost is also taken into account. Energy consumption for computation is so small comparing with energy consumption at packet transmissions. However, the proposed model causes extra computational cost of sensor nodes. So computational cost is considered for observing influence of duty cycle adjustment operations on energy consumption of the nodes. Energy consumption rates of TelosB and simulation parameters of XMAC are listed in Table 4.1 and Table 4.2.

Initial energy of each node is taken as $50J$. Initial duty cycle is assigned as 10%. c is taken as 0.8. Duty cycle adjustment is done every 20s period. Network continues to send packets from a source to destination until there is a network partition. Hence, we run simulations till a network partition occurs. Network partition is tested after the death of each node by the breadth first search algorithm. Multiple nodes generally send their measurements to the sink in WSNs. So sources are selected according to uniform distribution in each packet generation time.

Table 4.1: XMAC values employed.

| Variable of XMAC | Duration |
|---------------------------------------------------|----------|
| Preamble (S_p) | 2 ms |
| ACK listen and ACK send (R_a and S_{al}) | 2ms |
| Sender data and receiver data (S_d and R_d) | 4 ms |

Table 4.2: Energy consumption of TelosB nodes.

| Operation | Energy Consumption |
|-------------------------|--------------------|
| Transmit for 1 ms | 54 mW |
| Listen for 1 ms | 60 mW |
| Receive for 1ms | 61 mW |
| Sleep for 1ms | 35 μ W |
| Compute for 1 T_{CLK} | 1.2 nJ |

4.2 Results for Forwarder Set Based Dynamic Duty Cycling

We tested the proposed forwarder set based dynamic duty cycling model with a grid topology. 36 nodes are deployed in $60 \times 60 m^2$ grid topology with inter node distance of $10m$. Transmission range of each node is taken as $15m$. Degree of the nodes can change from three to eight. Sensor nodes are placed left-bottom corner to the right-top corner of the grid row by row with increasing IDs as shown in Fig. 4.1. The sink is the node with ID# 0. Sources are chosen from all the WSN with uniform distribution. The network traffic is negative exponentially distributed. The mean of distribution is $1s$ and the observed minimum inter packet generation time set as $250ms$. All sources try to send its packets to sink node with ID# 0. Topology can be seen in Fig. 4.1.

When we study the results, we observe that if sources are chosen randomly among all nodes in the topology, delay performance gives high fluctuations. Because packets that are generated by the nodes closer to the sink, experience lower delays and such results could be misleading. Therefore, we decide to select the sources with uniform distribution from right-top quarter part of the topology and right part of the topology in a part of the evaluations shown with the dashed lines rectangle in Fig 4.1. Finally we also evaluated the results for different source selection cases. We evaluate the simulations results for the network lifetime, remaining energy of nodes and end-to-end delay.

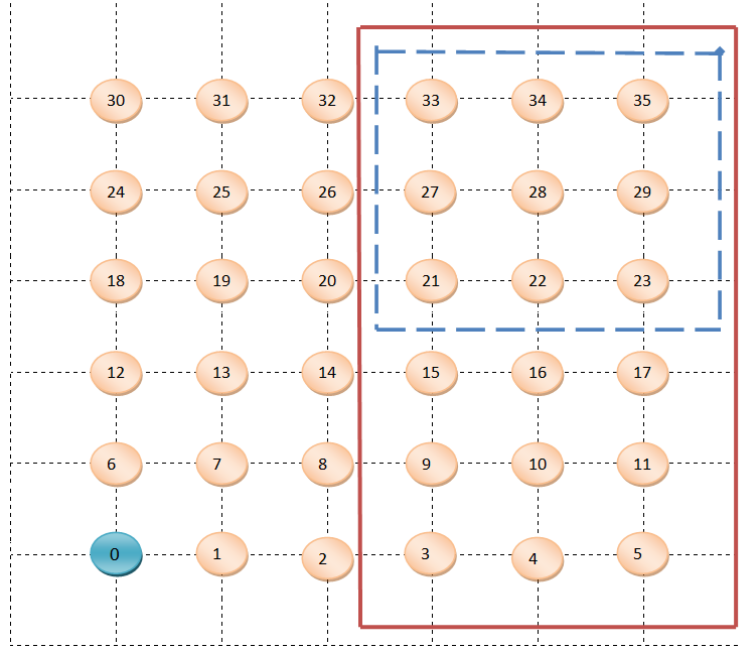


Figure 4.1: The grid topology employed.

We compare the proposed forwarder set based duty cycle scheme with the node degree based heterogeneous duty cycling technique [33] and constant duty cycling. Initially, the same duty cycles are assigned to all nodes as in constant duty cycle scheme. Duty cycles of the nodes are not changed during the lifetime of the network. In [33], each node updates its duty cycle as in (4.1) where d_0 is initial duty cycle of the node. Degree of a node is updated if the node discovers new neighbours. β is a tunable parameter taken as $\frac{1}{2}$. If node has higher degree, then it decreases its duty cycle. It is not applicable for WSNs with static sensor nodes. Because degree of the node does not give information about network dynamics during network lifetime. Node degree is determined in network deployment phase. So node degree based duty cycling scheme is not robust to network dynamics.

$$d_i = d_0 \times (\text{degree}(i))^{-\beta} \quad (4.1)$$

4.2.1 Network lifetime

Network lifetimes of the three techniques are compared. Results for each scenario are obtained from 20 iterations. In our simulations, if a node is not dead when network partition occurs, the lifetime of the node is taken equal to the time of network partition, since we stop simulation. Black dashed line represents the mean network lifetime of 20

iterations. Green line is the mean lifetime of each node in the topology. Furthermore % 95 confidence interval of lifetime of each node is plotted with error bars.

In constant duty cycle scheme, lifetimes of nodes are close to each other. Critical nodes that are close to sink, have depleted their energy. So the network lifetime ends dramatically in a short time. The network lifetime is limited with the death of critical nodes.

The node degree based duty cycle scheme shows longer lifetime results. Here, the lifetimes of the critical nodes are increased by using alternative paths. Duty cycle of high degree nodes are decreased. Then lifetimes of high degree nodes are increased. Packets are forwarded by other nodes with higher delay.

The scheme gives approximately 2 times longer lifetime compared with the node degree method and 6 times longer lifetime compared with constant duty cycling. It shows that following the higher energy consumption of critical nodes, the other nodes, that are one-hop distance to them, become receiver in next packet transmissions. We obtained lifetime extension by balancing traffic load of critical nodes in the forwarder set. Thus, we try to extend the lifetime of highly-used nodes.

The nodes that does not transmit so many packets and be in the forwarder set in contention period generally trend to increase its duty cycle depend on the proposed scheme. This adjustment increases chance of being winner in the contention period. On the other hand, increasing the duty cycle also causes the energy depletion of the nodes as drawback. Therefore death of these type of nodes that are not in critical positions in the WSN, does not affect packet transmissions. In Fig.4.2, the lifetime of nodes in right-top part of the grid topology can be shorter. But network is not divided by the dead of the nodes on right-top part.

In Fig 4.2, the nodes in left-top of the grid topology, are not used in packet transmissions frequently. So their duty cycles are not adjusted at duty cycle adjustment periods that have no packet transmissions. If the node does not transmit a packet after 3s, it decreases its duty cycle dramatically. So the lifetimes of nodes in left-top of grid topology are longer comparing with other nodes in topology. The lifetime of nodes can be various depend on network topology or network dynamics as seen in the evaluation.

Finally the proposed scheme gets longer lifetime by balancing energy consumption among critical nodes.

4.2.2 Delay

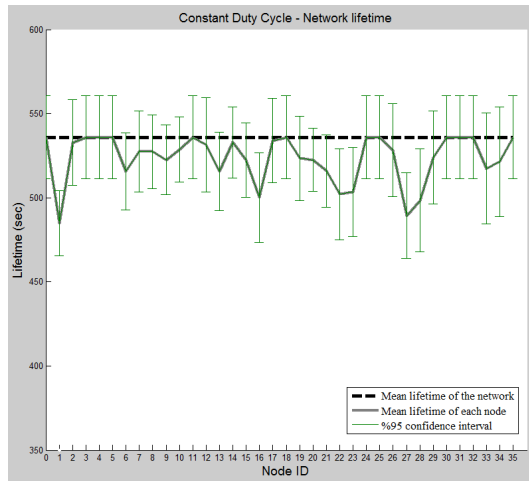
In Fig. 4.3, mean delay and error bars with % 95 confidence interval are plotted for 10 iterations. The best delay performance is obtained with constant duty cycle as expected. Here, nodes select the closer nodes to sink and the duty cycles of all nodes are fixed. So the chances of the neighbouring nodes to be the next hop are the same.

Dynamic duty cycling schemes try to supply alternative paths for packet transmission. Packets can be forwarded through longer paths by using less used nodes in packet transmission. So delay can increase by dynamic duty cycling schemes. Therefore dynamic duty cycling schemes has higher delay results comparing with constant duty cycling.

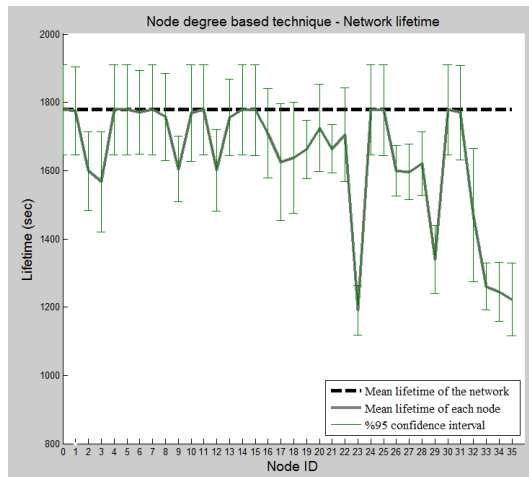
Node degree based dynamic duty cycle aims to improve worst case end-to-end delay and its mean delay is slightly higher than the mean delay of constant duty cycle scheme. The scheme has closer mean delay time to the node degree based scheme as shown in Fig. 4.3. The scheme prevents longer delays by providing at least one node with higher duty cycle in the forwarder set. α is used for mean probability of being the next hop. So the duty cycle adjustment is done based on balancing energy consumption in forwarder set basically. Hence, packets can be transmitted by higher duty cycled nodes. So the end-to-end delay performance is not degraded significantly comparing with constant duty cycling.

4.2.3 Remaining energy of sensor nodes

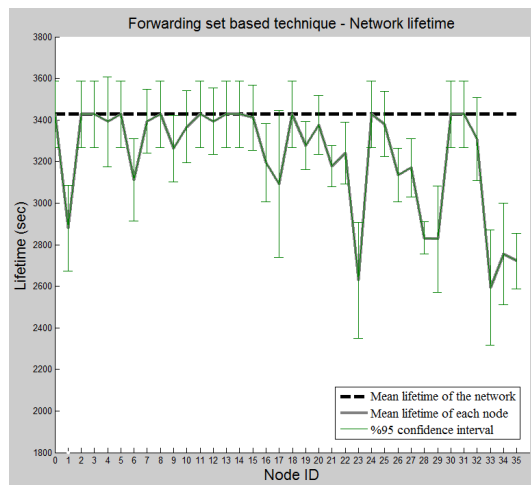
In Fig. 4.4., the remaining energy of the nodes is shown following the network partition. The nodes are placed as in Fig.4.1. The lines above the bar of the remaining energy represent % 95 confidence interval. Remaining energy of the nodes that are close to sink and sources (right-tops quarters of the topology), is decreased dramatically in all of the three techniques. Because these nodes are highly-used nodes in packet transmissions.



(a) Constant duty cycling.



(b) Node degree based technique.



(c) Forwarder set based technique.

Figure 4.2: Network lifetime of three techniques.

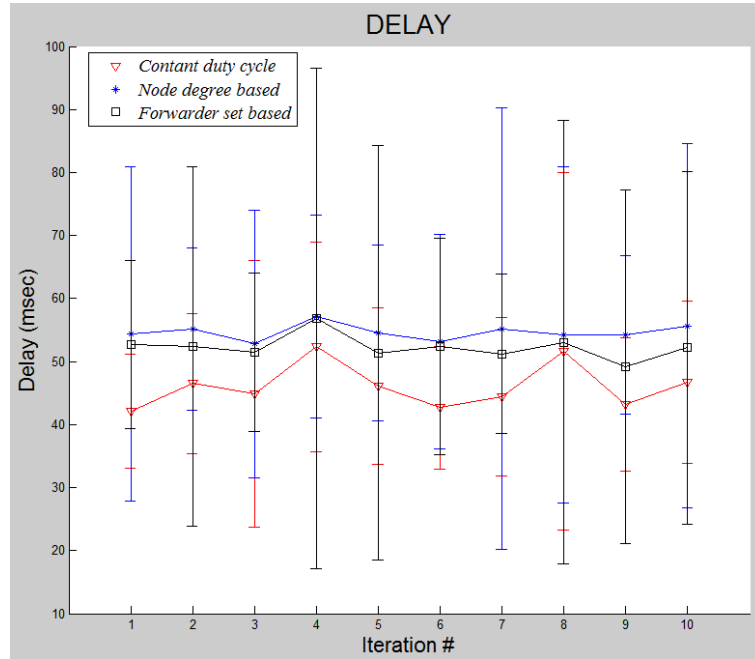


Figure 4.3: Delay of three techniques.

In constant duty cycling, the remaining energy of the living nodes generally is higher than the other techniques. Since the communication stops after the death of the critical nodes and the other nodes still have a reasonable amount of energy.

The node degree based duty cycling technique causes energy depletion of nodes, except the corner nodes that do not have a chance to be source. The nodes that are closer to sink nodes have not depleted their energy before network lifetime. The reason is preamble sending and duty cycle adjustment. Nodes update their duty cycle based on node degree. The inner nodes in grid topology have lower duty cycles because of their high node degree. The nodes that behave as sources of the topology consume most of their energy on preamble sending. When any source node from the right-top part of the topology sends a packet, it needs to send so many preambles when waiting the wake-up time of potential receiver nodes. So inner nodes become to consume most of their energy in preamble sending.

The scheme also causes energy depletion of similar nodes with node degree-based dynamic duty cycling method. It is an expected result. It can be seen that the scheme resulted longer lifetime by using a higher portion of nodes in packet transmission. The proposed duty cycling scheme updates the duty cycle of the nodes by preventing a high number of preamble sending. Therefore, energy depletion of the nodes is postponed and network lifetime is prolonged.

The reason of higher confidence intervals in remaining energy of left-top of the grid topology and right-bottom part of the grid topology, are fluctuating number of packet transmission of these nodes. Other nodes in grid topology have smaller confidence interval values because of their highly usage in packet transmissions.

4.2.4 Source selection cases

As mentioned before, if sources are chosen among all nodes in WSNs, delay performance gives highly fluctuating results. In the previous simulations, the source nodes are selected randomly with uniform distribution from all of the WSN topology shown in Fig 4.1. In this section, the obtained results are based on the three cases considering the location of sources.

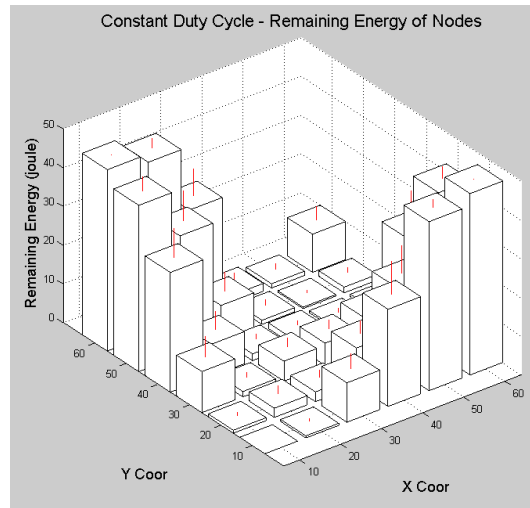
The three cases considering the location of sources are:

- Sources are from the upper right quarter (Quarter)
- Sources are from the right half (Half)
- All nodes can be a source except the sink node (Full).

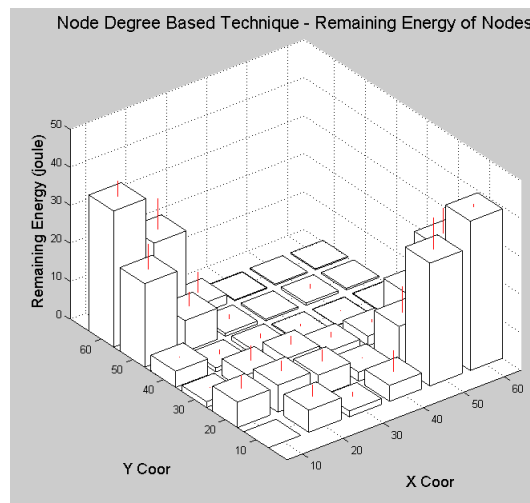
As seen in Fig. 4.5., the lifetime does not differ significantly as the source selection changes. The quarter case has slightly higher results compared to the other cases. The longer lifetime in Quarter case, is an expected evaluation result.

Sending a packet is one of the most energy consuming operations for sensor nodes. In Quarter case, less number of nodes are source and the location of these nodes are not close to sink. After a while, source nodes deplete their energy. However, network can tolerate the death of source nodes. Because source nodes that have long distance to sink, are not critical for network coverage.

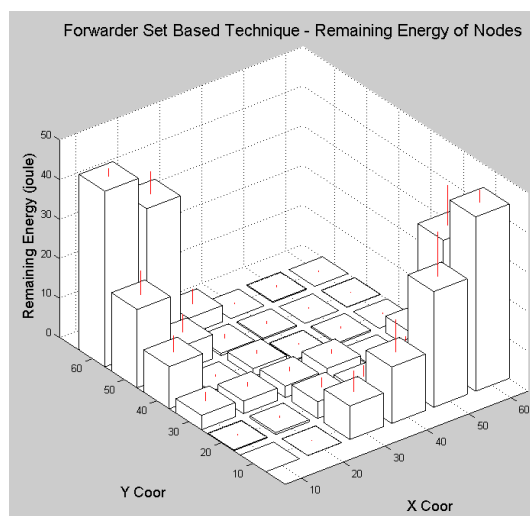
The difference among network lifetime for three techniques are not so different from each other. Because network lifetime metric in the evaluation is network partition. Network partition occurs when critical nodes deplete their energy. Dead times of critical nodes does not affect from source selection cases. However end-to-end of each packet gives more stable results in Quarter case comparing with Full case. In Full case, source node can be various hop distance to sink, then end-to-end delay of packets has fluctuating results.



(a) Constant duty cycling.



(b) Node degree based dynamic duty cycling technique.



(c) Forwarder set based dynamic duty cycling technique.

Figure 4.4: Remaining energy of each node for three techniques.

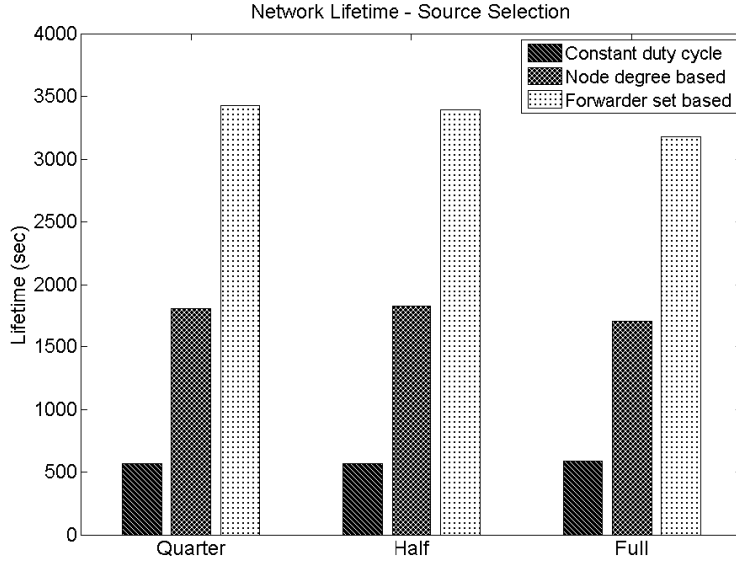


Figure 4.5: Performance of techniques under various source selection cases.

4.3 Results for Adaptive Sink Selection in Multi-sink Wireless Sensor Networks

We used a multi-sink WSN in the evaluations. In the test scenario, 144 nodes are deployed in $120 \times 120 m^2$ grid topology with inter node distance of $10m$ and transmission range of $15m$. It is assumed that sensor nodes know their exact location with the help of GPS or localization algorithms. There are four sinks that are placed in the corners of the WSN topology.

Each sensor node only knows the sink that is closest to itself and sends its packet to the closest sink node using the geographic forwarding technique. Sensor nodes have no information about the other sinks. Initially, each sink has a region of nodes which try to send their packets to itself. The grid topology which is employed in simulations is given in Fig. 4.6. Virtual regions are divided with dashed lines.

We do not adopt any network lifetime metric in the evaluations. For example, first node death as network lifetime is not efficient metric for multi-sink WSNs. As first node death does not prevent to packet transmissions to sinks notably in multi-sink WSNs. When network partition is set as network lifetime, adaptive sink selection in multi-sink WSNs cannot be observed especially after the dead of many nodes. Finally we defined a sufficient duration for the evaluations. Simulations are run until $4000s$ in the evaluations.

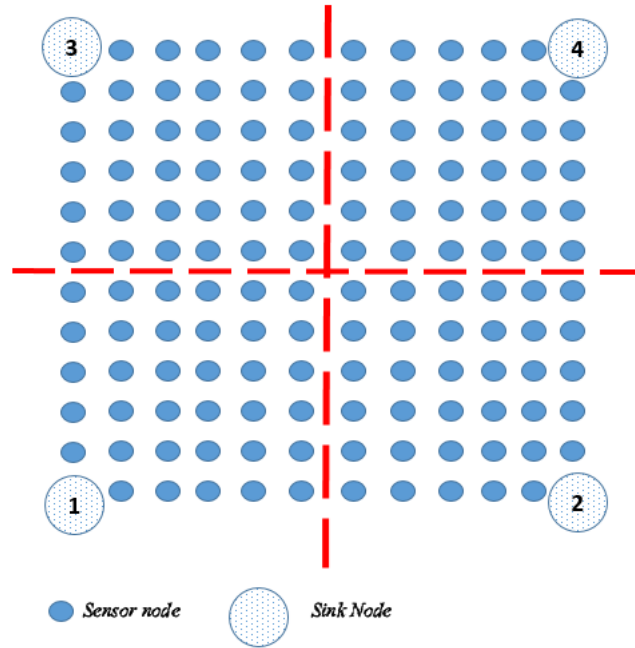


Figure 4.6: Multi-sink grid topology.

Poisson distribution is used for traffic generation because of its memoryless property. In the evaluations, an event occurs, then packets generate for the event and send to sink node. The network traffic is created based on Poisson distribution. The mean distribution rate is taken as 1pkts/s . There is no queue on the sensor nodes due to low traffic rate. Nodes send their measurements to the sink. Sources are selected according to uniform distribution in each packet generation time.

4.3.1 Node failure scenarios

We created routing holes in node failure scenarios, Because proposed model reroutes the packets to other sinks and performance of proposed model can be observed by routing holes accurately.

No failure scenario and four different node failure scenarios are used in the evaluations. Broken nodes (red nodes) and their position in the topology are shown in Fig 4.7. Nodes fail at various times in each scenario. In order to obtain more accurate results, all of the failed nodes in the scenarios are broken before 500 second of simulation time. Flexible limit set as 2 in no failure scenario, Scenario#1 and Scenario#2 and as 5 in Scenario#3 and Scenario#4. Since the failed nodes in Scenario# 3 and Scenario# 4, are closer to Sink4 than in Scenario#1 and Scenario#2.

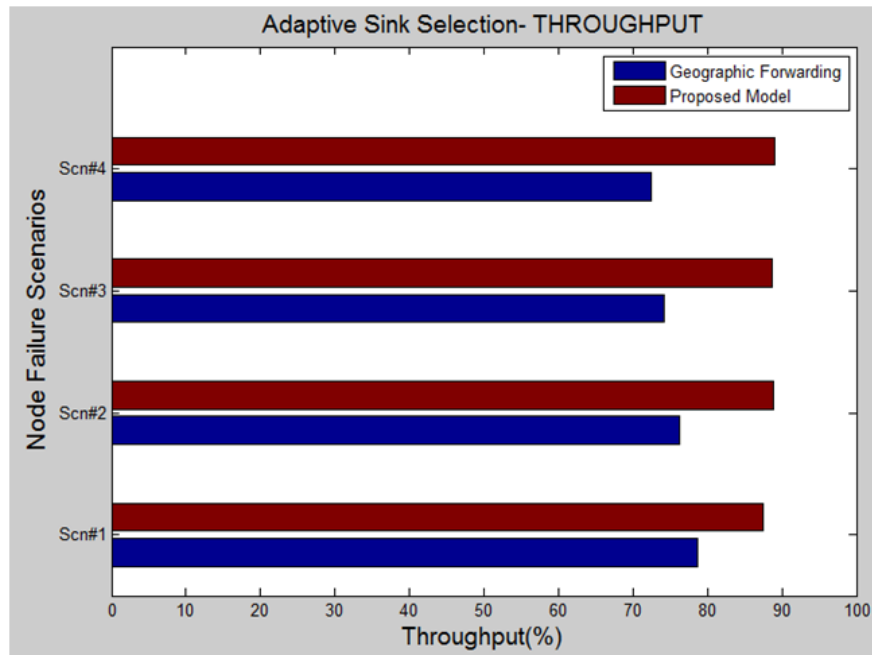


Figure 4.8: Throughput obtained by proposed technique and geographic forwarding.

4.3.2 Throughput

The motivation of the proposed model is to reduce the number of lost packets observed with the geographic forwarding technique when node failures are occurred in WSN.

As shown in Fig 4.8., the proposed model achieves higher throughput in node failure scenarios. Each sink has virtual regions that consist of nodes whose closest sink is itself. When a routing hole occurred in the region of Sink 4, the nodes in region of Node 4 cannot send its packet through to closest sink. Packet loss rate increases dramatically. In geographic forwarding, packet loss rate is approximately 25%. The proposed techniques aims to reduce packet loss in the case of routing holes by re-routing the packets to another sinks.

Distance of the routing hole to sink node increases step by step from Scenario#1 to Scenario#4. The proposed model reroutes the packets to another sinks successively and increases throughput in the case of routing hole. Throughput is increased sufficiently by estimating node failures and rerouting the packets to another sinks in each node failure scenario.

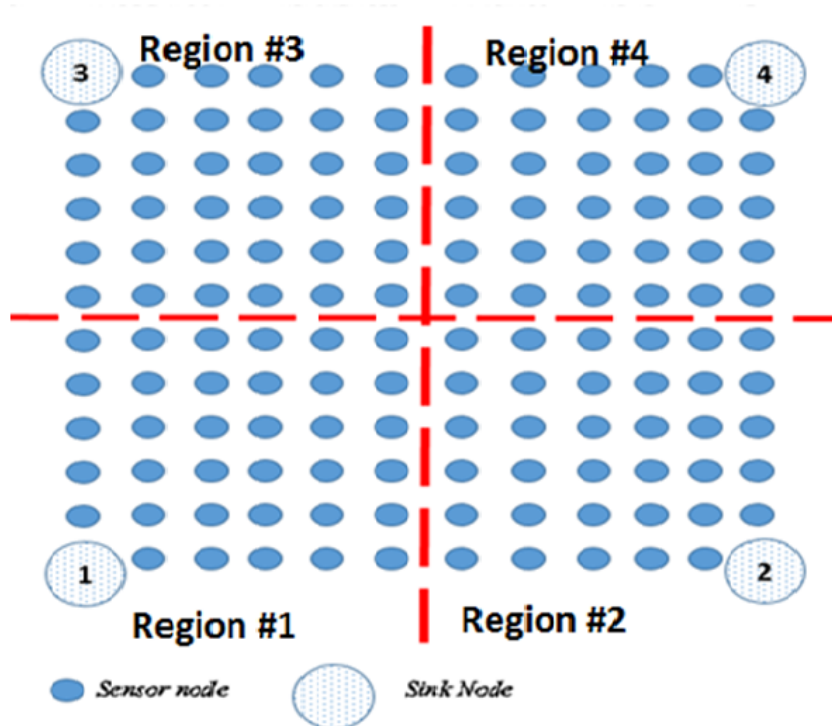


Figure 4.9: Virtual regions are created by the sinks.

4.3.3 Delay

In the proposed scheme, the packets are sent to the other sinks in order to reduce the packet drop rate in case of node failures. Naturally, as the number of hops necessary to the sink increases, the end-to-end delay also increases. Here, degradation in delay is tolerable compared with reduced packet loss rates. Furthermore TTL (time-to-live) is set for each node for preventing longer E2E (end to end) delay. If the packet forwarded through longer paths as result of specious estimations about node failure, packets are dropped after reaching TTL.

When re-routing the packets to other sinks, number of hops between source and destination increases. Delay degradation comparing to geographic forwarding is an expected result. So delay performance among the virtual regions is compared. In Fig. 4.9, virtual regions that are created by sink nodes are presented. For instance, the closest sink of the nodes in Region#1 is Sink 1. Then the region that consists of the nodes whose closest sink is Sink 1, is named as Region#1.

In Fig. 4.10, delay performance of four region is compared. E2E delay of Region#4 is higher than the other regions due to routing holes occurred in the Region#4. E2E delay

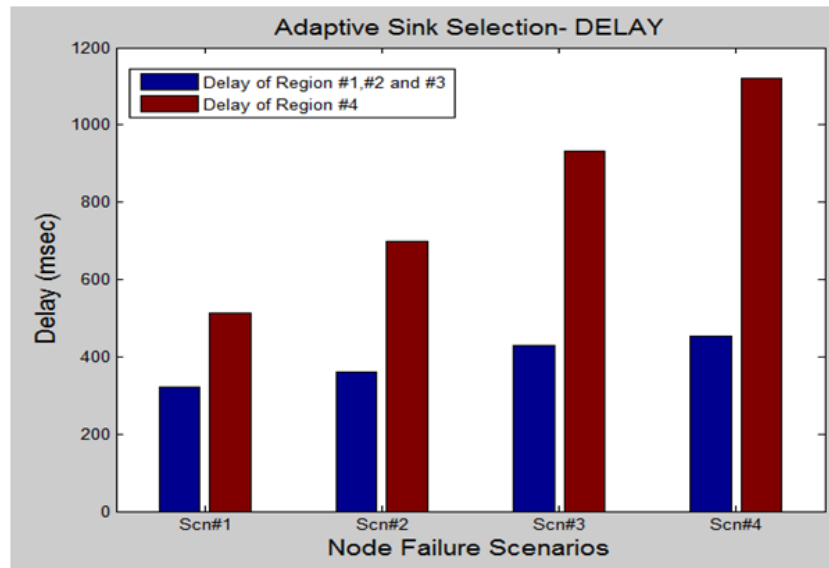


Figure 4.10: Delay obtained by the proposed technique for virtual regions.

of Region#4 is the highest in Scenario#4 comparing to other node failure scenarios. Because routing holes occurred closer to sink than the other node failure scenarios. Therefore more number of hops between source and destination are observed when re-routing the packets to another sinks.

Highest delay performance of Region#1,#2 and #3 is also observed in Scenario#4. Number of rerouted packets increases, when routing hole occurs closer to the sink. Then, traffic rate in other regions increases due to rerouted packets. Therefore E2E delay of Region#1,#2 and #3 increases as the results of higher traffic rate in their region.

5. CONCLUSIONS AND FUTURE WORK

This thesis presents a research on self-organizing WSNs. Nodes set their duty cycles and forwarder sets based on the statistics that are obtained from network layer. Because coordination among neighbour nodes needs packet transmission and cause the communication overhead. Furthermore communication with the sink for coordination are not robust to large-scale WSNs.

Firstly, we proposed a forwarder set based dynamic duty cycling scheme. Duty cycling is widely used for energy efficiency. Dynamic duty cycle adjustment is proposed for energy balance and prolonging the network lifetime. Nodes does not need to communicate their neighbours when they update their duty cycles. They update their duty cycle based on being in forwarder set, winning the contention period and remaining energy. We compared proposed model with constant duty cycling and node degree based duty cycling. The proposed dynamic duty cycling scheme outperforms constant duty cycling with six times longer lifetime and node degree based duty cycling with two times longer lifetime. Moreover, remaining energy of nodes after network partition is more balanced in the proposed model comparing with constant duty cycling and node degree based duty cycling. Delay performance is not degraded significantly compared with constant duty cycling. Also the proposed model gets similar delay performance with node degree based duty cycling scheme.

Secondly, adaptive sink selection is done by each sensor node in the case of node failures for multi-sink WSNs. Our aim is preventing packet loss due to routing holes and node failures. The proposed model re-routed the packets to another sinks and prevents packet loss in a self-organizing manner. When the node has a packet to transmit, it sends preambles. After sending N_{max} preambles, the node *feels* the failure in its forwarder set or routing hole. Therefore, the node complements its forwarding set and tries to send the packet to any of its neighbours. The simulation results showed that the proposed scheme outperforms the geographic forwarding technique in the scenarios that contain node failures. Node can forward the packet to another node

and packets can be re-routed to other sinks. Packets begin to be rerouted to other sinks in the proposed model. Throughput performance is increased due to preventing packet loss comparing with geographic forwarding. Otherwise, E2E delay performance is degraded our model comparing with geographic forwarding. It is an expected result. Because packets are rerouted to the sinks that are not the closest sink. Therefore hop count is increased between source and destination. Degradation in end-to-end delay performance is tolerable compared with packet loss.

Finally, we proposed two methods. The main purpose of first one is obtaining energy balancing in WSN by duty cycle adjustment. The aim of the second one is to make the sensor nodes failure resistant. We aim to propose models that work in distributed manner to prevent communication overhead.

5.1 Future Work

As the future work, the analysis can be extended to propose a mathematical model for improving performance of the network with less number of preambles. The forwarder set based duty cycle scheme will be studied extensively by simulation under higher traffic rates, ultra low duty cycled nodes by using some other heterogeneous topologies.

Furthermore, we are planning to fine tune the detection of node failures by varying the number of preambles, N_{max} , and using some other parameters obtained from the sensor nodes. We try to develop mathematical model for *feeling* node failures in WSN.

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