Development of an Energy and Geographic Aware Opportunistic Network Coding Scheme

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***Abstract*—Mobile Ad-Hoc Networks and Wireless Sensor Networks are communication networks that consist of nodes with limited energy resources. Therefore, routing protocols implemented in such networks need to be aware of the energy levels in a network to enable them to route in an energy effective manner. Network Coding (NC) is a technique that optimises the throughput of a network. In this paper we investigate the effect of power failure of energy-constraint nodes on network throughput, and propose a NC scheme that not only increases the throughput of a network as opposed to traditional routing mechanisms, but also does so in an energy effective manner. The proposed scheme incorporates geo-routing into one of the leading NC schemes, CORE, and while it delivers more throughput than CORE, it also focusses on energy awareness resulting in extended lifespans of nodes in a network. The NC scheme is implemented and simulated in OMNET++ and the results show significant improvement in both network throughput and lifespan of nodes.**

***Index Terms*—Energy Awareness, Geo-Routing, Mobile Ad-Hoc Network, Network Coding, Opportunistic Routing, Wireless Sensor Network.**

I. Introduction

The evolution of communication networks has led us to an era where you cannot only perform surgery halfway across the world, but do so while being in the comfort of your own home. By eliminating the need for wires, wireless networks revolutionized communication networks by enabling nodes to communicate while being in a mobile state. The concept opened many doors to new applications and possibilities. Wireless Ad-Hoc Networks are networks formed by wireless nodes. They are self-established and do not depend on any infrastructure.

Mobile Ad-Hoc Networks (MANETs) and Wireless Sensor Networks (WSNs) are wireless communication networks that consist of nodes with limited energy resources [1], [2]. Nodes need energy to transmit, receive and process data. When a node is drained of all its energy resources, it cannot perform any functions and is of no use to the network, or in the case of user operated nodes, the operating client. It is imperative that nodes in such networks remain alive for as long as possible, especially in WSNs where each node is responsible for monitoring a specific area or item [3]. Therefore, routing protocols implemented in such networks need to be energy aware. Energy awareness in networks refers to the monitoring of the energy levels of nodes, or the calculation of the amount of energy required per transmission, and using the acquired data as deciding factors when performing routing.

Network Coding (NC) is a technique that optimises the throughput of a network by coding packets [4]. NC can be divided into two categories namely deterministic NC and opportunistic NC [5]. In deterministic NC (DNC), coding opportunities are determined beforehand, and nodes are then assigned encoding and decoding roles. DNC is therefore heavily dependant on the network topology. In opportunistic NC, nodes calculate the local coding opportunities using the available information acquired from neighbour nodes. Opportunistic routing is the preferred option when routing in MANETs, since the topologies in such networks are dynamic.

Opportunistic routing (OR) is a technique that allows routing without prior knowledge of the exact next-hop node; hence OR routes opportunistically as opposed to fixed-path routing protocols [6]. In OR, there is a small pause before each transmission. The pause can be exploited to include routing conditions to be considered before performing further routing.

Geo-Routing (GR) refers to routing based on the geographical coordinates of nodes [7].

In this paper we investigate the effect of energy-constrained nodes on a network, and propose a NC scheme that not only increases the throughput of a network as opposed to traditional routing mechanisms, but also does so in an energy effective manner. The proposed scheme incorporates GR into one of the leading NC schemes, CORE, and while it delivers more throughput as CORE, it also focusses on energy awareness resulting in extended life spans of nodes in a network. The NC scheme is implemented and simulated in OMNET++ and the results show significant improvement in prolonging the lifetime of a node.

The remainder of this paper is arranged as follows: In section II, we give background on MANETs, WSNs, OR, GR and NC. In section III, we discuss related work, specifically COPE and CORE. Section IV presents the NC scheme after which the implementation is explained in section V. The simulation parameters are discussed in section VI, followed by the results and discussion thereof. A conclusion is drawn in section VII and we take a look at future work in section VIII.

II. Background

A. Mobile Ad-Hoc Networks (MANETs)

MANETs are self established, infrastructureless ad-hoc networks that consist of mobile nodes [8]. The term 'mobile node' refers to any mobile device with communication abilities such as a laptop or smartphone. Mobile devices are limited with regard to their transmission ranges, processing capabilities and energy resources [2]. The fact that nodes in MANETs have limited energy resources, necessitates custom routing protocols dedicated to preserve energy. MANET topologies can change randomly at any given moment due to the mobility of the nodes.

B. Wireless Sensor Networks (WSNs)

The primary use for WSNs is to retrieve real-time information from the environment such as temperature, geographical characteristics and particulate matter (e.g. CO_2). A WSN consists of sensor nodes and base stations (sinks). The sensor nodes are responsible for acquiring data from the environment, processing the data and transmitting information to the base stations [9]. The base stations integrate and combine the data collected from the sensor nodes to produce useful information. Sensor nodes are usually battery powered and it is therefore essential that WSNs operate and communicate in an energy-efficient manner in order to keep the nodes alive for as long as possible [1], [10]. Environment, medical healthcare and military monitoring are only a few of the fields included in WSN applications.

C. Opportunistic Routing (OR)

OR, unlike fixed path routing, does not specify each packet's next-hop node [6]. It calculates a forwarder set. The forwarder set of a packet contains nodes that are closer to the packet's destination according to a specific routing metric. Upon packet reception, each node in the forwarder set calculates a delay timer based on further criteria. Further criteria refer to conditions relevant to the objectives the routing protocol needs to accomplish. The objectives can be to increase robustness, optimise throughput or to conserve energy. The nodes with the better conditions will calculate a smaller delay and will therefore transmit sooner that the other nodes in the forwarder set.

When a node forwards a packet, the rest of the nodes in the forwarder set that overhears the packet will drop matching packets to prevent duplicate forwarding and unnecessary transmissions. OR is very effective in high packet-loss scenarios, since the probability of the entire forwarder set failing, is very slim. This incorporates a high level of robustness into the network [11].

D. Geo-Routing (GR)

GR refers to routing based on the geographical coordinates of nodes [7]. Nodes with a smaller geo-distance to the destination node, in comparison with the sender node, forward the packets. GR can only be implemented in networks where the nodes know their own coordinates. Nodes can acquire geographical coordinate information by GPS or localisation techniques.

E. Network Coding (NC)

NC refers to the concept of coding multiple packets into a single coded packet to optimise throughput [4]. This technique enables us to transmit multiple packets in a single transmission; hence transmitting more data for the same number of transmissions or requiring less transmissions to send the same amount of data, when compared to traditional routing mechanisms. NC increases network throughput to the theoretic maximum achievable throughput as can be calculated using the min-cut max-flow theorem [12], [13].

The theorem states that the maximum throughput achievable in a network, is equal to the minimum cut between the source and the destination nodes in a network, where there are no flow capabilities between the source and the destination. The theorem is explained in figure 1. In this scenario, source node S wants to send packets **a** and **b** to destination nodes X and Y. The minimum cut between source node S and destination nodes X and Y, is **two**. Therefore the maximum throughput obtainable in this network is **two**. After a full round of transmissions, **three** packets reached the destination nodes. **Two** packets were sent. This translates to a suboptimal throughput of **1.5** (3/2).

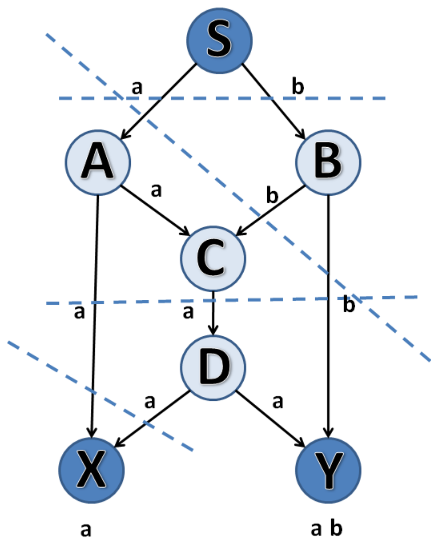

Fig. 1. Min-cut max-flow theorem

When NC is implemented, the throughput increases to **two**, as shown in figure 2. In this scenario, packets **a** and **b** are encoded at node C. The NC packet is sent in a single transmission to node D, and delivered to the destination nodes X and Y in the next transmission. The destination nodes then use the packets they have overheard from previous transmissions in order to decode the NC packet. In this scenario, **four** packets have reached the destination nodes, and it translates to a throughput of **two** (4/2), which is the maximum obtainable throughput of the network. The following example explains the concept in more detail.

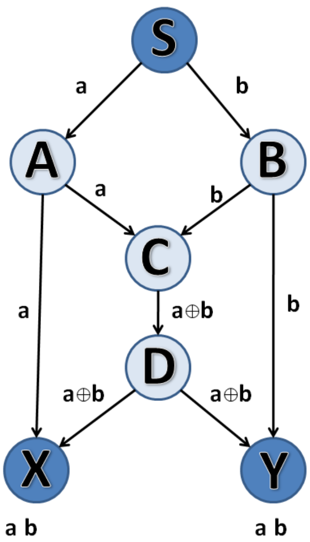

Fig. 2. Network with Network Coding

A single NC packet is created by means of XORing individual packets with each other. A NC packet is decoded by being XORed with a sufficient number of different individual packets it's comprised of. Please refer to figure 3.

Packet (1) and (2) respectively represents packets **a** and **b** from the previous example, depicted in figure 2. The NC packet comprised of the two packets are represented by packet (3). By XORing either of packets (1) or (2) with the NC packet (3) will decode the NC packet and deliver the other packet as illustrated in (4) and (5).

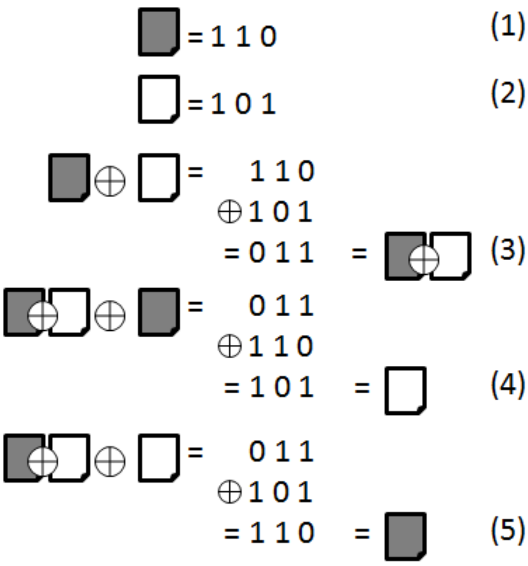

Fig. 3. Network Coding in detail

F. *Opportunistic Network Coding (ONC)*

In ONC, NC opportunities are calculated dynamically at each forwarder node by using the acquired neighbour information [4], [14]. This type of coding scheme is very effective in MANETs, since the network topology of such networks are dynamic. COPE and CORE are examples of ONC.

III. Related Work

A. *COPE*

COPE, presented in [4], is the first practical implementation of ONC. The NC scheme proves to deliver significant throughput gain as opposed to traditional routing schemes, in some cases even up to 400% increase. COPE employs three key elements namely *opportunistic listening*, *opportunistic coding* and *learning neighbour state*. The three elements work as follows.

Opportunistic listening - In wireless networks, any node close enough to a node that transmits, may overhear the transmission. This characteristic is exploited by enabling nodes to store and process those overheard packets. Nodes can then use the overheard packets for various purposes. One of those purposes is to decode coded packets. Each node is configured to temporarily store all overheard packets for a default time of T = 0.5s.

Opportunistic coding - Opportunistic coding refers to the intelligence in coding as many packets as possible, so that all the destination nodes can decode the coded packet with their stored packets, in order to retrieve the native packet intended for them. In order to discover and perform the best possible packet combination in opportunistic coding, it is essential that the NC node knows which packets each of its neighbour nodes has.

Learning neighbour state - Reception reports are appended to data packets. The reports contain information regarding the stored packets at the sender node. In this way, nodes can learn what packets are stored at their neighbours and are enabled to perform optimal coding accordingly.

Please refer to figure 4 for an example on COPE. By means of reception reports, node A knows which packets are stored by its neighbour nodes. Using this information, node A can decide to XOR packets $P1$, $P2$ and $P3$. Now, all the neighbour nodes can successfully decode the coded packets and retrieve the native packets intended for them.

Whilst COPE is opportunistic with regard to performing NC, it still lacks opportunistic features with regard to the paths the packets travel. Although the packets are coded opportunistically, the paths that they travel remain fixed. The fixed-path routing mechanism creates a limitation in the process of calculating coding opportunities, since the calculating node may only code packets that can be decoded at the **fixed** next-hops. This allows scenarios where packets are sent on suboptimal paths. CORE alleviate this shortcoming by incorporating OR into the scheme.

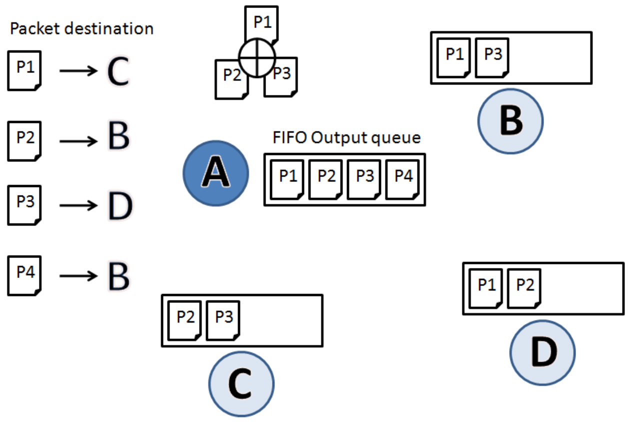

Fig. 4. COPE Network Coding

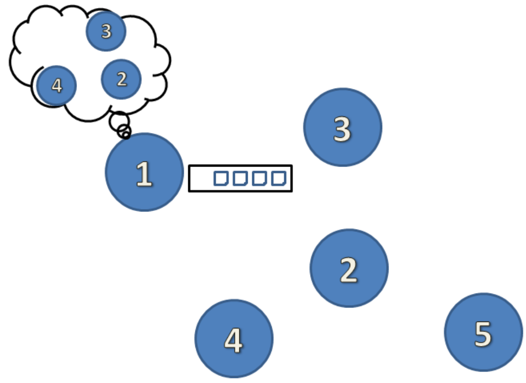

Fig. 5. Forwarder set

B. CORE

CORE, presented in [14], is based on COPE and shares the same three key elements namely *opportunistic listening*, *opportunistic coding* and *learning neighbour state*. Instead of routing packets on fixed paths as in COPE, CORE enables nodes to opportunistically forward packets without specifying the precise next-hop node. As in OR, CORE first selects a forwarder set. In this case, nodes have to be geographically closer to the destination node to be accepted into the forwarder set. The criteria prioritising the forwarder nodes are the number of local coding opportunities each node calculated. The nodes with more coding opportunities will have a smaller delay and therefore transmit packets sooner than nodes with less coding opportunities. Upon hearing forwarded packets, nodes in the forwarder set can cross-reference the sent packets with packets in their own queue and drop them accordingly to prevent duplicate forwarding.

Please refer to figure 5. In this scenario, node 1 has a packet for destination node 5. In COPE, only node 2 would be considered as the next-hop node and therefore only node 2 would be included in the coding opportunity calculation procedure. In CORE, node 1 calculates a forwarder set, in this case nodes 2, 3 and 4, which are all considered when calculating coding opportunities.

IV. Network Coding Scheme Design

We propose a geographic and energy aware NC scheme based on CORE [14]. The scheme adds geographic and energy conditions to the CORE scheme, and is made up of three key elements namely *forwarder set selection*, *priority based forwarding* and *coding opportunity calculation*. The design exploits the *priority based forwarding* aspect to include geographic and energy based conditions.

Forwarder set selection - If a node has a packet to send, it first selects a forwarder set. Nodes must comply with the following prerequisites to be included in the forwarder set:

- Must be a neighbour node
- Must be geographically closer to the destination
- Node may not exist in the packet's previous forwarder set

As in OR, the forwarder set is a list of nodes of which one will eventually become the forwarder of the packet. This set of nodes is the only nodes considered when calculating coding opportunities.

Coding opportunity calculation - When calculating coding opportunities, k number of enqueued packets are considered along with the first packet in the queue (the **primary** packet). The variable k can be adjusted to increase or reduce processing intensity. The deciding node knows what packets its neighbours have due to reception reports. It can therefore cross-reference different combinations of coded packets with the packets its neighbour nodes has and calculate the **code gain** of each combination. The **code gain** refers to the number of nodes that can decode the coded packet and retrieve a packet intended for them. The combination that delivers the most gains is referred to as the **maximum gain**. The packets are coded according to the combination that delivers the **maximum gain**.

Priority based forwarding - The **maximum gain** obtained in the previous step is one of the conditions used to calculate the delay the node must wait before it transmits. The delay is calculated by dividing a time interval, in this case 5ms, by the **maximum gain**. Nodes with more coding opportunities will have a smaller delay; hence transmit their packets sooner.

The delay value is now adjusted correspondingly by observing the energy levels of the nodes in the forwarder set. The adjustment is made to ensure that nodes with similar coding opportunities but with higher energy levels transmit sooner. The delay is adjusted further by taking into account this node's geographical distance to the destination node. Closer nodes will have smaller delays. When a forwarder set node transmits, the other nodes in the same forwarder set that overhear the packet will drop matching ones to prevent duplicate forwarding.

V. Network Model

The network model is discussed in this section. The network model is build in OMNET++. Each node is equipped with an

802.11b MAC layer, with a coding layer stacked on top. The rest of the upper layers are as they appear in the OSI stack. The upper layers are responsible for generating traffic. As for the *MAC layer* and *network layer*, they work as follows.

- *MAC layer* - The 802.11b standard is implemented in the MAC layer. It was modified to send all overheard packets to the network layer for processing. It was also modified to receive packet cancellation control messages from the network layer. The network layer sends cancellation messages to the MAC layer to indicate that the packet to be sent must be dropped.
- *Network layer* - The network layer performs all the coding and routing operations and is responsible for the following:

1 *forwarder set selection* - Calculating the forwarder set of the packet.
2 *opportunistic coding* - Calculating the local coding opportunities and knowing when to search for new opportunities on packet reception.
3 *priority based forwarding* - Calculating the delay timer based on the coding, geographic and energy based conditions.
4 Dropping packets from the queue in order to prevent duplicate forwarding in the forwarder set. This task is accomplished by sending down cancellation messages to the MAC layer.

VI. Simulation Results

Simulation parameters and results are discussed in this section. The NC scheme was simulated in OMNET++. One of the simulated networks is depicted in figure 6. Each node displays its battery status. The yellow warning sign indicates a dead node.

For simulation purposes, 200 nodes were deployed in an 800 X 800 m^2 square area. The nodes were placed at random coordinates inside the area. The channel rate was configured as 11 Mbps. The variable k was set to 10. UDP flows varying from 200kbps to 2Mbps was generated. The offered load was regulated by adjusting the number of flows. Five random topologies were used for each simulation setting.

The first simulation compares the throughput of CORE with and without the geographic condition. By incorporating the geographic condition, a throughput increase of as much as $1.3Mbps$ (23% throughput gain) can be achieved. The results are depicted in figure 7 and are summarised in table 1 with regard to percentage throughput increase, averages and maximum throughput.

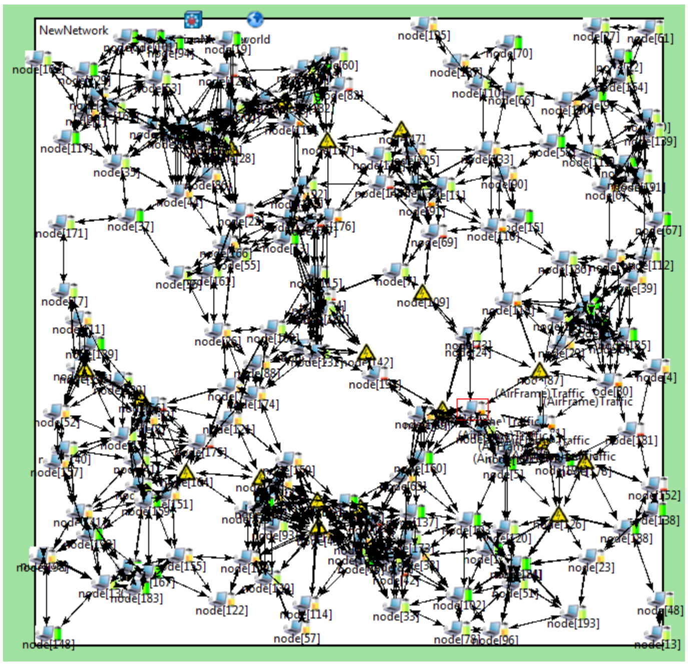

Fig. 6. OMNET network topology

Table 1. Throughput comparison of CORE with and without geographic based conditions

	CORE	**geo-CORE**		
Load (Mbps)	Through-put (Mbps)	Through-put (Mbps)	% Throughput increase	
2	1.7	1.8	5.88	
4	3.4	3.6	5.88	
6	4.3	4.9	13.95	
8	5.6	6	7.14	
10	5.7	7.02	23.16	
11	5.18	5.5	6.18	
12	4.8	5.4	12.50	
13	3.36	4.58	36.31	
8.25	4.255	4.85	13.88	**Average**
10	5.7	7.02	23.16	**Maximum throughput**

The second simulation evaluates the number of node deaths in time intervals. The nodes were given random low battery statuses to avoid unnecessary long simulation times. The energy levels assigned to the nodes allowed an average of five to 20 data transmissions per node. The incorporation of energy based conditions displayed significant improvement in node survivability. The results are depicted in figure 8.

VII. Conclusion

In this paper, one of the key elements in CORE, prioritized forwarding, is exploited to improve network throughput and create an energy aware, geo-aware NC scheme. The scheme combines the benefits of NC with geo-distance and energy

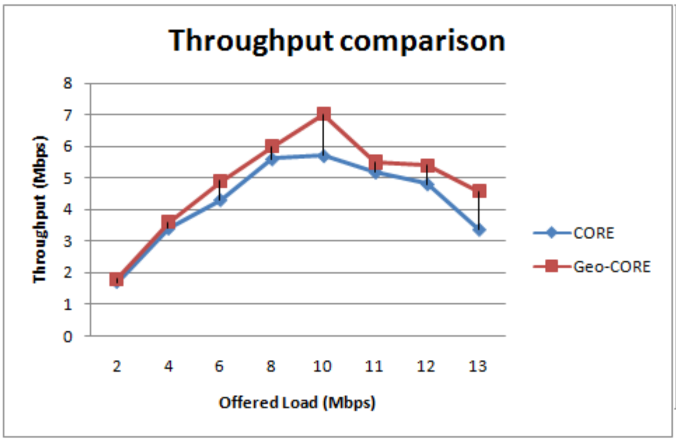

Fig. 7. Throughput comparison of CORE with and without geographic based conditions

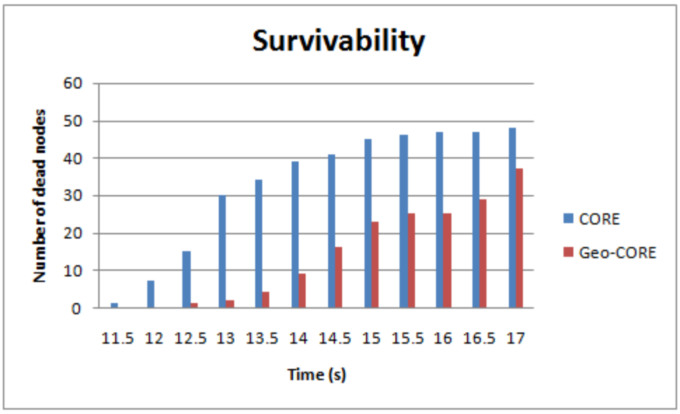

Fig. 8. Survivability of nodes when implementing CORE with and without energy based conditions

aware path routing to create an effective NC scheme for networks where energy efficiency and high throughput are imperative requirements. The simulation results showed a throughput gain of up to 23% and significant increase in node survivability.

VIII. Future Work

By changing the conditions of the *priority based forwarding* delay calculation, a routing protocol was enhanced with improved throughput and energy efficiency. By changing current conditions or even by introducing new ones, many more limitations and network characteristics can be addressed. Future work includes researching different combinations of current and new prioritising conditions for priority based forwarding to further improve the NC scheme, especially with regard to the mobility characteristics of the network.

IX. Acknowledgements

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References

[1] S. Wang, X. Gao, and L. Zhuo, "Survey of network coding and its benefits in energy saving over wireless sensor networks," in *Information, Communications and Signal Processing, 2009. ICICS 2009. 7th International Conference on*, dec. 2009, pp. 1 –5.

[2] Y. Yoo and D. P. Agrawal, "Why does it pay to be selfish in a manet?" *Wireless Communications, IEEE*, vol. 13, no. 6, pp. 87 –97, dec. 2006.

[3] P. K. Sahoo and J.-P. Sheu, "Limited mobility coverage and connectivity maintenance protocols for wireless sensor networks," *Computer Networks*, vol. 55, no. 13, pp. 2856 – 2872, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128611002167

[4] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "Xors in the air: Practical wireless network coding," *Networking, IEEE/ACM Transactions on*, vol. 16, no. 3, pp. 497 –510, 2008.

[5] M. Grobler and A. Helberg, "Identifying opportunities for deterministic network coding in wireless mesh networks," *SAIEE African Research Journal*, vol. 102, pp. 8 – 15, 2011.

[6] S. Biswas and R. Morris, "Opportunistic routing in multi-hop wireless networks," *SIGCOMM Comput. Commun. Rev.*, vol. 34, pp. 69–74, January 2004. [Online]. Available: http://doi.acm.org/10.1145/972374.972387

[7] M. Zorzi and R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: multihop performance," *Mobile Computing, IEEE Transactions on*, vol. 2, no. 4, pp. 337 – 348, 2003.

[8] P. Yang and B. Huang, "Multi-path routing protocol for mobile ad hoc network," in *Computer Science and Software Engineering, 2008 International Conference on*, vol. 4, dec. 2008, pp. 1024 –1027.

[9] V. Potdar, A. Sharif, and E. Chang, "Wireless sensor networks: A survey," in *Advanced Information Networking and Applications Workshops, 2009. WAINA '09. International Conference on*, may 2009, pp. 636 – 641.

[10] W. Li, J. Bao, and W. Shen, "Collaborative wireless sensor networks: A survey," in *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference on*, oct. 2011, pp. 2614 –2619.

[11] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, "Trading structure for randomness in wireless opportunistic routing," *Computer Communication Review*, vol. 37, no. 4, pp. 169–180, OCT 2007.

[12] B. A. Forouzan, *Data Communications and Networking*, 4th ed. McGraw-Hill, 2007.

[13] S. Wang, X. Gao, and L. Zhuo, "Survey of network coding and its benefits in energy saving over wireless sensor networks," in *Information, Communications and Signal Processing, 2009. ICICS 2009. 7th International Conference on*, 2009, pp. 1 –5.

[14] Y. Yan, B. Zhang, J. Zheng, and J. Ma, "Core: A coding-aware opportunistic routing mechanism for wireless mesh networks [accepted from open call]," *Wireless Communications, IEEE*, vol. 17, no. 3, pp. 96 –103, 2010.

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