Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 94 (2016) 288 – 294

Procedia Computer Science

The 11th International Conference on Future Networks and Communications (FNC 2016)

A Survey on Energy Efficient Network Coding for Multi-hop Routing in Wireless Sensor Networks

M.E. Migabo[a,*], K. Djouani[a,b], T.O. Olwal[a], A.M. Kurien[a]

[a] F'SATI, Tshwane University of Technology(TUT), Staatsartillerie Road, Pretoria 0001, South Africa
[b] LISSI, University of Paris Est Creitel (UPEC), Paris, France

Abstract

Network coding consists of intelligently aggregating data packets by means of binary or linear combinations. Recently, network coding has been proposed as a complementary solution for energy efficient multi-hop routing in Wireless Sensor Networks (WSNs). This is because network coding, through the aggregation of packets, considerably reduces the number of transmissions throughout the network. Although numerous network coding techniques for energy efficient routing have been developed in the literature, not much is known about a single survey article reporting on such energy efficient network coding within multi-hop WSNs. As a result, this paper addresses this gap by first classifying and discussing the recent developed energy efficient network coding techniques. The paper then identifies and explains open research opportunities based on analysis of merits of such techniques. This survey aims at providing the reader with a brief and concise idea on the current state-of-art research on network coding mainly focusing on its applications for energy efficient WSNs.

Peer-review under responsibility of the Conference Program Chairs

Keywords: Wireless Sensor Networks; Aggregating; Network Coding; Energy Efficiency; Random; Linear; Coding Opportunities; Coding Challenges; Coding Metrics.

1. Introduction

The limited energy resource is known to be one of the major issues faced by WSNs. In addition to the energy problem, WSNs just like any other wireless networks suffer from a variety of unique problems such as low throughput, little or no connectivity and inadequate support for mobility out of range[3]. In most multi-hop routing, information packets are broadcast in order to update the network's status so as to improve throughput, enhance connectivity and enable high mobility. Although information broadcasts require very little computation at the level of sensor nodes, duplications of packets (resulting in considerable energy wastage, load imbalance, high network traffic and low network throughput) are often common. Fortunately, the modern sensor nodes have been equipped with fast and powerful processors that can make possible network coding implementation. Such network coding techniques are capable of trading more computation for smart techniques to aggregate packets in order to reduce the number of transmissions thereby lowing the overall energy wastage in the WSN.

* Corresponding author. Tel.: +27-12-382-5452 ; fax: +27-12-382-5294.
E-mail address: migabo.emmanuel@gmail.com

Peer-review under responsibility of the Conference Program Chairs
doi:10.1016/j.procs.2016.08.043

Conventionally, network coding has been considered as one of the possible solutions to the current energy wastage, low throughput, non-connectivity and mobility support problems in WSNs. However, practical challenges facing the integration of such designs into the network stack remain unresolved in the literature[14]. The network coding challenges arise when attempting to simultaneously achieve low complexity, fast coding, small memory usage, high data rates and adaptation to the unknown channel conditions[3]. Of these challenges, fast coding, compulsory reliability and real time constraint are specific to energy efficient network coding for multi-hop routing in WSNs. They are discussed as follows.

1.1. Fast coding

While the complexity of the *inter-flow* coding is usually low, the computation cost of the linear *intra-flow* coding in WSNs is most often expensive. In most cases, linear encoding algorithms require polynomial time complexity. This polynomial time complexity has been proven to be bounded to $O(n^2)$ with n being the number of linearly combined packets and considerably increases the computational energy consumption of sensor nodes.

1.2. Compulsory reliability

The transmission reliability of the encoded packet is mandatory for a successful operation of any network coding algorithm. Therefore, receiving $n-1$ linear combinations of n linearly combined packets is practically useless because successful decoding of an encoded packet requires at least n encoded packets. Should, reliable transmission not be guaranteed, more retransmission attempts are experienced and therefore more energy is wasted.

1.3. Real time constraint

The decoding of packets is only possible upon collection of at least n linearly combined packets. This naturally introduces time delays in the operation of the WSN and results in high energy consumption[4].

Based on these key challenges, this paper contributes in classifying and discussing some of the recently proposed energy efficient network coding techniques by identifying their merits and demerits towards creating future research opportunities.

The rest of the paper is organised as follows. Section 2 classifies and discusses energy efficient network coding for multi-hops routing in WSNs. In section 3, network coding metrics are presented. Section 4 analyses the energy efficient network coding opportunities in multi-hop WSNs and Section 5 concludes the paper.

Throughout the paper, we adopt the following nomenclature:

Nomenclature

WSNs	Wireless Sensor Networks	**GF**	Galois Field	**NACK**	Negative Acknowledge
RLNC	Random Linear Network Coding	**GBR**	Gradient Based Routing	**PDR**	Packet Delivery Ratio

2. Energy efficient Network coding protocols for multi-hop WSNs

There are two main classification approaches for the existing network coding techniques for muti-hop routing in WSNs. On one hand, network coding protocols in WSNs can be classified as **local** or **global** coding depending on whether the decoding of aggregated packets is performed at each sensor node level or only at destination nodes level respectively[5]. On the other hand, network coding techniques for muti-hop routing in WSNs can be classified as **intra-session** or **inter-session** depending on whether the relay sensor nodes only encode packets from the **same session** (source nodes) or encode packets from **different sessions** (sources). Most often, the intra-session network coding protocols in WSNs are designed to address the packet loss problem while the inter-session network coding protocols are designed in order to reduce the number of packets transmissions. Both network coding protocols classified as local or global can be further classified as either be **binary** (*XOR*) or **Random Linear** (*RL*).

Some of the most commonly known network coding approaches for WSNs are discussed as follows.

2.1. The COPR approach

COPR is a local (distributed) inter-session network coding approach in WSNs which is based on the well-known backpressure routing algorithm. COPR was developed in order to enhance the energy-efficiency of the backpressure algorithm. COPR has been proven to achieve up to 25% power saving over pure routing [7]. However, COPR still suffers from high computing complexity in its session scheduling [15].

2.2. The SenseCode approach

This network coding approach has been proposed by Keller [8] in order to simultaneously achieve reliable and energy-efficient data aggregation in WSNs. In SenseCode, it is assumed that the sensing task is performed by sensor nodes on a periodic basis. SensedCode then argues that the traditional tree-based Collection Tree Protocol (CTP) protocol as detailed by Gnawali [16], in which each intermediate node transmits the received packets from its children nodes to its parent, does not provide reliabile communication. The reason is that in case of node or link failures, the data will not be able to reach the sink node. Therefore, SenseCode proposes that the sensed data is transmitted through multiple paths instead of a single one. When implemented as a TinyOS module and evaluated through TOSSIM simulations, SenseCode has proven to reduce the end-to-end packet error rate by 90% under normal network conditions. It reliability drops to a value between 60% and 75 % in highly dynamic environments. In both scenarios, SenseCode maintains an average energy efficiency improvement of 10% as compared to the Collection Tree Protocol [8]. However, SenseCode suffers from a connectivity problem because under highly dynamic network conditions at least 10% of the sensor nodes are disconnected from the rest of the WSN [8].

2.3. The CodeDrip protocol

CodeDrip is a data dissemination protocol for WSNs which uses Network coding in order to improve energy efficiency, reliability and dissemination speed [13]. The CodeDrip protocol uses a Trickle timer to time the message transmissions to ensure that these arrive at all the nodes in the network. It is an enhancement of the Drip protocol [17] which modifies the Drip packet format in order to accommodate the control fields required by the decoding process. Its advantages include its high resilience to dissemination failure and its fast dissemination. However, CodeDrip is not such a suitable network coding protocol to be used in applications with high volume of sensed data. Through a series of experiments, CodeDrip has demonstrated to be faster, smaller than the Drip protocol.

Possibilities for further studies with CodeDrip include analysing the impact of different topology types and link qualities on the energy efficiency performance. Another interesting work is to develop new policies for combining messages using less complex operators as less complex operations means less computation which simply means less processing energy consumption.

2.4. Gradient Based Routing protocol with Network Coding (GBR-NC)

The GBR-NC protocol can be classified as an inter-session and local network coding protocol. One part of the GBR protocol operation consists of flooding of the interest messages by the sink node throughout the network. This process is done by broadcasting results in many unnecessary packet duplications which consequently results in significant energy loss [9].

The reception of a packet in WSN is a probabilistic event. This is mainly due to the stochastic nature of the wireless communication channel. Attempting to achieve energy efficiency by encoding (aggregating) packets with no guaranty of decoding them can lead to totally achieving the opposite (considerable energy wastage). Therefore, it is very crucial that the design of a network coding protocol considers the reliability aspect in order to achieve the network coding potential.

One of the GBR-NC principal drawbacks is the selection of the network coding scheme in order to achieve reliable network coding. Previous studies have demonstrated that a proper selection of the network coding scheme informed by the networks connectivity conditions can considerably improve the probability of successful decoding and therefore improves the WSNs energy efficiency.

When a sensor node wants to transmit n accumulated data packets $(P_1, P_2, P_3, ..., P_n)$, it first randomly selects n random coefficients $C_1, C_2, C_1, ..., C_n$ from the Galois Field of order 2^S with S being a positive integer. It then linearly combines the accumulated data packets together with the randomly generated coefficients can be computed as:

$$E = \sum_{i=1}^{n} P_i C_i \quad (1)$$

The decoding process on the receiver's side is conditional to the reception of a number of data packets $m \geq n$. Upon reception of m data packets, the decoding process is performed by Gaussian elimination process in which the accumulated header data (coefficients) are grouped to form a $n \times n$ matrix $C_{n \times n}$ which is then reduced to a row-echelon form. The n encoded data packets from the transmitter sensor node can be decoded by solving a set of linear equations provided that the obtained equations are linearly independent from each other which means that their coefficient vectors must be linearly independent. This is one key difference between the deterministic linear network coding technique and the RLNC as the randomness of coding coefficients increases the probability of their linear independence.

It was also experimentally proven by Doherty [10] that the larger the Galois Field, the higher the probability of linear Independence of its elements (Coding coefficients) as concisely summarised in table below.

Order	Probability	Order	Probability	Order	Probability	Order	Probability
2^1	0.288788	2^4	0.933595	2^7	0.992126	2^{10}	0.999022
2^2	0.688538	2^5	0.967773	2^8	0.996078	2^{11}	0.999511
2^3	0.859406	2^6	0.984131	2^9	0.998043	2^{12}	0.999756

Table 1. Probability of linear independence as a function of the Galois Field size

From the above table, it can clearly be shown that with a Galois Field of order 2^8 order, achieving linear independence is quite reliable (99.6%). This is one of the major reasons why RLNC is preferred for network Coding within WSNs as these are usually limited in terms of storage capacity [18].

A quick reasoning shows that in a network coding scenario, a sensor node sending one single encoded interest message instead of **n** messages that it receives saves up to $\frac{(N-1)}{N}$ bandwidth as compared to the traditional store-and-forward scenario. In addition, in a GBR scenario, network coding can considerably reduce the overall number of interest messages transmissions and therefore reduces the overall energy consumption of the WSN as follows,

2.4.1. Broadcasting of interest messages ***without Network coding***

For a WSN with a total of r sensor nodes including the sink node, assuming that the sink node possesses a total of N interest messages, from a case by case analysis, a general formula to compute the total number of transmissions T_{tot} can be derived as

$$T_{tot} = N(\frac{r-1}{2}) \quad (2)$$

2.4.2. Broadcasting of interest messages ***with Network coding*** *of network coding N*

From a case by case analysis, a general formula for the total number of transmissions has been T_{totNC} can be derived as

$$T_{totNC} = N + (\frac{r-3}{2})\ . \quad (3)$$

In short, the GBR-Network Coding (GBR-NC) algorithm mainly consists of a control mechanism to cater for shortage of sufficient packets for decoding to occur at the receiver sensor node. The drawback of this corrective method is that it becomes non-feasible with changes in the WSN connectivity.

2.5. ***MORE***

The MORE network coding approach is a Random Linear and opportunistic routing method as proposed by Chachulski[11], which can be used for both unicast and multicast applications. The MORE approach was developed in order to improve the throughput performance of the network. Field tests on a 25-nodes WSN testbed has proven that the median throughput gain of MORE compared to the traditional single path routing approach (with no network coding) is of 1.6. However, the opportunistic nature of the MORE protocol which creates its lack of coordination considerably are susceptible to affect its reliability performance and could cause its non-feasibility in certain applications. Evaluating such an impact could constitute a good subject for future work.

3. Network Coding metrics for multi-hop WSNs

Just like network routing protocols for WSNs, network coding protocols mainly aim at achieving energy efficiency, fast dissemination of data throughout the network, minimum data packets loss, reliable decoding of encoded packets at the receiving node and high throughput. The performance of a network coding approach for wireless sensor networks is usually evaluated in terms of the following communication performance metrics:

3.1. ***Average Packet Delivery Ratio (Average PDR)***

This metric is closely related to the throughput metric. The difference between the two is that instead of evaluating the number of successfully decoded packets over time; it evaluates the successfully decoded packets against the overall number of transmitted packets. The average PDR is a mean value and is therefore evaluated for all sensor nodes in the WSNs.

3.2. ***Packets dissemination latency***

This metric consists of how long it takes for encoded data to be transmitted from source node(s) to predetermined destination node(s). It a very important metric which measures how fast the coding and decoding processes take for a particular network coding protocol. It is also a way to evaluate the level of complexity of the considered network coding protocol. The packet dissemination latency becomes a crucial network coding metric to be considered in the design and performance evaluation phases of a network coding protocol for real-time WSNs applications. Current research work has proven that for a WSN with n nodes, the dissemination latency is expected to be between $O(n)$ and $O(n^2)$, depending on the reception probabilities of the nodes[6].

3.3. ***Network Resilience***

Network resilience is described as a multi dimensional metric taking parameters such as Average Delivery Ratio, Delay Efficiency, Energy Efficiency, Average Throughput and Delivery Fairness into account. Resilience evaluation is often graphically represented by means of a *kiviat diagram* which is each time created by means previous weighted parameters[12].

In summary, Table 2 provides a quick classification and comparison of some of the well-known network coding techniques in terms of some of the network coding metrics as described in section 3

4. Energy efficient network coding opportunities in multi-hop WSNs

The following opportunities can be exploited through network coding in order to enhance the overall performance of WSNs.

4.1. *Data aggregation*

Network coding is a form of data compression. By matching data packets from different sensor nodes, the relay sensor node can deliver multiple packets in a single transmission. When the data packets differ in their next hop

Network coding approaches	Classification	Advantages	Disadvantages
COPR	Local & Inter-session Random Linear	Strong network resilience	High complexity High dissemination Latency Low to Medium PDR
SenseCode	Local & Inter-session Binary (Physical)	High Average PDR Low dissemination latency	Poor Network resilience Connectivity problems
CodeDrip	Inter-session & Local Random Linear	Low dissemination latency Strong network resilience (Reliable)	Low to Medium PDR
GBR-NC	Local & Inter-session Random Linear	Low complexity Reliable: Strong network resilience	Medium to High dissemination latency
MORE	Global, Intra-session & Random Linear & Random Linear	Very high PDR	Poor reliability Poor network resilience High dissemination latency

Table 2. Summary comparison of network coding approaches in terms of network coding metrics

destinations, the matching is referred to as inter-flow network coding. Otherwise, the matching is referred to as intra-flow network coding. In both cases, more data is delivered in less number of transmissions which means more data is transmitted in less time.

4.2. Reduction of information packets in mobile WSNs

In mobile WSNs applications where the network configuration changes quickly, routing updates are usually costly in terms of energy and other resources. Network coding can be used to address the uncertainty in the network's topology and can therefore considerably alleviate the need for exchanging routing update packets.

4.2.1. Mobility

In mobile WSNs applications where the network configuration changes quickly, routing updates are usually costly in terms of energy and other resources. Network coding can be used to address the uncertainty in the network's topology and can therefore considerably alleviate the need for exchanging routing update packets.

Other opportunities that can be exploited by means of network coding in WSNs include reliability with no retransmission of lost packets, fairness by combining network coding and broadcasting in order to allow proper handling of data rates that the receivers experience over short time periods as elaborated by Christina Fragouli [3].

5. Conclusion

In summary, this paper has explored the different types of network coding protocols for multi-hop routing in WSNs. It has also further outlined the different research opportunities presented by network coding based on the analysis of the merits and demerits of the current techniques. It can form part of essential tools for research on the development of a network coding techniques in WSNs applications.

In addition to providing ideas and not detailed mathematical modelling of some of the most common network coding techniques used in WSNs, this survey paper clearly highlights the advantages as well as disadvantages of each of the network coding approaches. In a very special way, this paper provides a clear analysis of each of the identified advantages and disadvantages of these approaches and then identifies and formulates research opportunities from the derived analysis. This paper therefore constitutes a very essential tool to start with when exploring the field of network coding as applied in Wireless Sensor Network Coding.

Further study would include a much more detailed survey on classification and a much more detailed comparison study between the different network coding techniques in terms of their energy efficiency performance when applied to WSNs.

References

1. Y. Yang, C. Zhong, Y. Sun and J. Yang , *Energy Efficient Reliable Multi-path Routing Using Network Coding for Sensor Network*, In the Proc. of the International Journal of Computer Science and Network Security (IJCSNS), December 2008; 8(12), pp. 329-338
2. R. Ahlswede, N. Cai, S.R. Li and R.W. Yeung, *Network Information Flow*, In the Proc. of the IEEE Transactions on Information Theory, July 2000; 46(4), pp. 1204-1216.
3. C. Fragouli, D. Katabi, A. Markopoulou, H. Rahul and M. Medard, *Wireless Network Coding:Opportunities and Challenges*, In the Proc. of the Military Communications IEEE Conference, (MILCOM), Orlando, FL, USA, 2007; pp. 1-8.
4. S.P. Kumar, *Real-time Wireless Sensor Networks*, Thesis for Doctor of Philosophy degree in Computer Science, University of Virginia, Virginia, USA, 2007; 1.
5. P. Ostovari, J. Wu and A. Khreishah, *Network Coding Techniques for Wireless and Sensor Networks*, in the book by Habib, M.A, *The Art of Wireless Sensor Networks*, Springer Signals and Communication Technology, Michigan, USA, 2014; 1, pp. 129-162.
6. M.H. Firooz, *Data Dissemination in Wireless Networks with Network Coding*, In the IEEE Communications Letters journal, 2013; 17(5), pp. 944-947.
7. T. Cui, L. Chen and T. Ho, *Energy efficient opportunistic network coding for wireless networks*, In the Proc. of the 27th Conference on Computer Communications (INFOCOM2008), Phoenix, AZ, USA; pp. 1022-1030.
8. L. Keller, E. Atsan, K. Argyraki and C. Fragouli, *SenseCode: Network coding for reliable sensor networks*, In a final year Technical Report, EPFL, switzerland, 2009.
9. L. Miao, K. Djouani, A.M. Kurien and G. Noel, *Network coding and competitive approach for gradient based routing in wireless sensor networks*, in the Ad Hocs Networks journal, Elsevier Science Direct, 2012; 10 (6), pp. 9901008.
10. L. Doherty, B.A. Warneke, B.E. Boser and K.S.J. Pister, *Energy and performance considerations for smart dust*, In the Proc. of the Int. journal of Parallel and Distributed Systems and Networks, 2001; 4(3), pp. 121-133.
11. S. Chachulski, M. Jennings, S. Katti and D. Katabi, *Trading structure for randomness in wireless opportunistic routing*, In the Computer communication review (ACMSIGCOMM2007), 2007; 37(4), pp. 169-180.
12. P. Brunisholz, M. Minier and F. Valois, *The Gain of Network Coding in Wireless Sensor Networking*, In the HAL open access archive, 8 Dec 2014; Lyon Univeristy (INRIA lab) research report, 8650, pp. 1-19.
13. N.R. Junior, M.A.M. Vieira and L.F.M. Vieira, *CodeDrip: Data Dissemination Protocol with Network Coding for Wireless Sensor Networks*, In the Proceedings of the 11th European Conference, EWSN 2014, Oxford, UK, February 17-19, 2014; 8354, pp. 34-49.
14. A. R. Lehman and E. Lehman, *Network coding: Does the model need tuning?,* SODA, 2005; pp. 499-504.
15. T. Cui, L. Chen, and T. Ho, *Energy efficient opportunistic network coding for wireless networks,* Caltech, Tech. Rep., July 2007.
16. O. Gnawali, R. Fonseca, K. Jamieson, D. Moss and P. Levis, *Collection tree protocol,* In the Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems, ACM, New York, USA, 2009; pp. 1-14.
17. Q. Yuan and J. Wu, *Drip: A dynamic voronoi regions-based publish/subscribe protocol in mobile networks,* In INFOCOM 2008, April 2008; pp. 2110-2118.
18. G.J. Poittie and L.P. Clare, *Wireless integrated network sensors: toward low-cost and robust self-organizing security networks,* In the Proc. of the SPIE conf. on Sensors, C31, Information and Training Technologies for Law reinforcement, 1999; 86(3577), pp. 1-7.