Performance of Network Coding Based Multipath Routing in Wireless Sensor Networks

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Abstract

In recent times, there have been many advances in the field of information theory and wireless sensor network (WSN) technologies. Network coding is a new paradigm in data transport and promises to change many aspects of WSN. In this paper, we introduce an analytical framework to study the performance of network coding based multipath routing, and proposes a Network Coding based Multipath Routing algorithm, in comparison with replication based multipath routing in WSN (NCMR). It is typically proposed in order to increase the reliability of data transmission or to provide load balancing. In our simulation, we compare NCMR routing protocol with AODVM and MDSR routing protocol, in terms of the packet delivery rate, average packet delivery delay, packet loss probability and network lifetime when a packet is transmitted. The simulation results show that the NCMR routing protocol provide an accurate and efficient method of estimating and evaluating the route stability in dynamic WSNs.

Keywords: *Wireless Sensor Network, Multipath Routing, Network Coding, Performance Evaluation.*

1. Introduction

Wireless sensor networks (WSNs) are characterized by a dynamic topology, limited channel bandwidth and limited power at the nodes. Because of these characteristics, paths connecting source nodes with destinations may be very unstable and go down at any tinle, making communication over WSNs difficult [1–12]. Therefore, the routing protocols for a WSN must be adaptive and capable of maintaining routes as the characteristics of the network connectivity change. Designing an efficient and reliable routing protocol for such networks is a challenging issue [1–12].

Most existing WSN routing protocols build and utilize only single route for each pair of source and destination nodes. Due to node power, node failures, and the dynamic characteristics of the radio channel, links in a route may become temporarily unavailable, making the route invalid. Multipath routing addresses this problem by providing more than one route to a destination node. Source and intermediate nodes can use these routes as primary and backup routes. Some previous works like CMQ of Rezaie [4], EBBCP of Kumar [5], AOMDV of Marina [6], multipath DSR (MDSR) of Nasipuri [7], and Lin in [8] make sure that the paths stored are “link disjoint” and do not have common hop between them, or “node disjoint” and thus have no common nodes in their paths. MDSR lets the destination check the route request packets RREQs it has received and the paths within them before sending RREPs back to the source with the most disjoint paths.

Network coding refers to the basic notion of performing coding operations on the contents of packets throughout a network, and is is generally attributed to Ahlswede et al. [9], who showed the utility of the network coding for multicast in wired networks. The work of Ahlswede et al. was followed by other work by Koetter and Medard [10] who showed that codes with a simple, linear structure were sufficient to achieve the capacity of multicast connections in lossless, wireline networks. This result was augmented by Ho et al. [11], who showed that, in fact a random construction of the linear codes was sufficient. Noguchi et al. [12] showed that network coding can balance the load of a network. Kagi et al. [13] proposed an efficient and reliable packet transmission method by using multipath routing constructs from multiple node disjoint routes, and by applying network coding, which allows packet encoding at a relay node. However, in network coding based multipath routing, one has to pay the price that any useful data can be decoded only after the destination receives a sufficient number of coded packets and can decode all data altogether.

In this paper, we propose an analytical framework to char acterize network coding based and replication based multipath routing protocols. Our analytical model demonstrates that the network coding based protocol delivers data with shorter delay when bandwidth is limited and such advantage is more significant when the buffer sizes are constrained.

The rest of the paper is organized as follows: In section 2, we briefly review the network coding related work. Section 3 presents network coding theorems in WSN. Some simulating results are provided in section 4. Finally, the paper concludes and future work in section 5.

2. Related Work

The value of the cut is the sum of the capacities of the edges on the cut. According to the multicast network problem statement, maximum flow from source to destinations in any network is equal to the size of min-cut [14]. With the proof of this multicast problem statement and by consideration of the network communication system model and its solution in terms of NC [15].

For example, a wireless network coding scheme depicted in Figure 1. In this example, two wireless nodes need to exchange packets *a* and *b* through a relay node. However, the network coding approach uses a store code and forward approach in which the two packets from the clients are combined by means of an XOR operation at the relay and broadcast to both clients simultaneously. The clients can then decode this coded packet to obtain the packets they need.

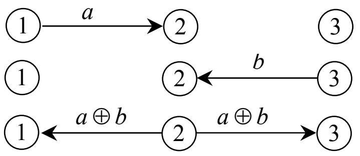

Fig. 1 WSN network coding.

The binary symbol $a \oplus b$ is a mathematical function of *a* and *b*. Calculation of a function from received data is called coding. This shows the merit of mixed coding among multiple messages at an intermediate node. This is called network coding (NC). In algebra, $a \oplus b$ is called the binary sum of *a* and *b*. Interpreting in more general terms of linear algebra, this is the linear sum $1 \bullet a + 1 \bullet b$ over the binary field. Thus, the calculation of $a \oplus b$ is not only a form of coding but also belongs to the more restricted form of linear coding.

Generally, routing refers to the flow of data packets from source node(s) to destination node(s) where intermediate node(s) simply replicate and forward without any processing on received packets. NC allows each node to perform an operation, for example linear combinations of received data packets before forwarding on different transmissionlines. Therefore, NC-aware routing is a special case of NC. NC-aware routing techniques take into account the availability of NC opportunities within a network during route selection for data transmission. Combining data packets from different flows along routes with more coding opportunities further improves network throughput.

Simply, NC-based routing deals with the recoding of packets belonging to the same flow and is also known as intra-flow or intra-session coding. Protocols, i.e. NC-RMR [16], and PipelineOR [17] are related to NC-based routing and the use of NC reduces redundant data transmissions that lead to energy consumption reduction within WSNs.

To address the issues related to the coding conditions and the number of packets to be coded Guo *et al.* [18] and Le *et al.* [19] analyzed the performance of practical coding schemes to determine the number of packets that can been coded. They also defined generalized conditions that sufficiently identify actual coding points within a wireless network which ultimately possess compatibility and availability.

3. Network Coding Theorems (NCT)

3.1 Network Model

This paper will discard such an unrealistic assumption, and develop a practicable model for network coding. For WSNs, we model the network as a directed hypergraph $H=(N, A)$, where N is the set of nodes and A is the set of hyperarcs. A hypergraph is a generalization of a graph where generalized arcs, called hyperarcs, connect two or more nodes. Thus a hyperarc is a pair (i, J), where i , the head, is an element of N, and J, the tail, is a non-empty subset of N. Each hyperarc (i, J) represents a lossy broadcast link. For each $K \subset J$, some disjoint subset of the packets injected into hyperarc (i, J) by node i are received by exactly the set of nodes K without error.

Consider the link corresponding to arc (i, j). Suppose the loss rate on this link is ε_{ij}, i.e. packets are lost independently with probability ε_{ij}. Suppose further that the injection of packets on arc (i, j) is described by the counting process B_{ij} and has average rate r_{ij}, i.e. $\lim_{\tau\to\infty} B_{ij}(\tau)/ =r_{ij}$ a.s. The parameters r_{ij} and ε_{ij} are not necessarily independent and may well be functions of each other.

For the arrival of received packets, we have

$$A_{ij(\tau)} = \sum_{k=1}^{B_{ij(\tau)}} X_k \tag{1}$$

where $\{X_k\}$ is a sequence of i.i.d. Bernoulli random variables with $\Pr(X_k = 0) = \varepsilon_{ij}$. Therefore

$$\lim_{\tau\to\infty}\frac{A_{ij(\tau)}}{\tau} = \lim_{\tau\to\infty}\frac{\sum_{k=1}^{B_{ij(\tau)}} X_k}{\tau} = \lim_{\tau\to\infty}\frac{\sum_{k=1}^{B_{ij(\tau)}} X_k}{B_{ij(\tau)}}\frac{B_{ij(\tau)}}{\tau} = (1-\varepsilon_{ij})r_{ij} \qquad (2)$$

which implies that

$$z_{ij} = (1-\varepsilon_{ij})r_{ij} \qquad (3)$$

3.2 Network Coding Theorems

The network coding idea was introduced by Ahlswede *et al*. [9]. Usually, the routers or relay nodes just forward and duplicate the packets in the networks. However, network coding permits routers or relay nodes to encode the packets. In this paper, we use a linear network coding scheme [20].

Encoding: The coding operation performed by each node is simple to describe and is the same for every node: received packets are stored into the node's memory, and packets are formed for injection with random linear combinations of its memory contents whenever a packet injection occurs on an outgoing link. The coefficients of the combination are drawn uniformly from F_q. The linear network coding scheme is an encoding method such that coding vector $g_i = (g_{i1}, g_{i2},\ldots, g_{iN})$ is given, and input packet $M = (M_1, M_2,\ldots, M_N)$ is converted into output packet P_i by the following expression [13].

$$P_i = \sum_{j=1}^{N} g_{ij} M_j \qquad (4)$$

The destination node can decode input packets because the coding vector $G = (g_1, g_2, \ldots, g_N)$ and output packet data $P = (P_1, P_2, \ldots, P_N)$ are obtained from the received packets, and an inverse matrix exists in G.

We see that any node that receives $\lfloor N(1+\varepsilon)\rfloor$ or more packets with linearlyindependent auxiliary encoding vectors has $\lfloor N(1+\varepsilon)\rfloor$ packets whose global encoding vectors collectively form a random $\lfloor N(1+\varepsilon)\rfloor$ × K matrix over F_q, with all entries chosen uniformly.

Decoding: Decoding at any receiver is performed by collecting packets of a given generation. These packets yield a system of linear equations that need to be solved to retrieve the original native packets. Suppose a node has received v encoded packets $X_1, X_2, \ldots, X_s$ belonging to a given generation, with $v \leq N$ while $g'_1, g'_2, \ldots, g'_v$ represent the coding vectors corresponding to the encoded packets. The generic element of the decoding matrix G is given by: $G_{ij} = g_{ij}$ where $i = 1, \ldots, s$ and $j = 1, \ldots, N$. Let us denote the rank of G by R. When the matrix has full rank, i.e., $R = s = N$, for a given generation, then the node can solve the linear equations to retrieve all native packets belonging to that generation. In this case, the receiver can recover part of the source native packets belonging to the given generation. We finally observe that when a node receives a packet, it must check whether it is innovative or not, i.e., whether it increases the rank of the decoding matrix G. If not, the packet is dropped.

Theorem 1. Consider the lossy wireless packet network (H, z). The random linear network coding scheme is capacity-achieving for multipath connections, i.e., for K sufficiently large, it can achieve, with arbitrarily small error probability, a multipath connection from source node S to sink nodes T at rate arbitrarily close to R_t packets per unit time for each $t \in T$ if

$$R_t \leq \min_{M \in M(s,t)} \{ \sum_{(i,j)\in\Gamma_+(M)} \sum_{K \not\subset M} z_{iJK} \} \qquad (5)$$

3.3 Node Operations

Our network coding-based multipath routing is implemented on top of the network layer running over an IEEE 802.11 MAC protocol. This choice allows us to avoid encoding routing address information carried in IP headers. The network coding header contains information about the encoded packet, such as: the generation size and identifier, the number of encoded packets along with their size, and the coding vector. Three different operations are performed when network coding is applied:

Source node operations. The source node's application layer generates native packets, which are then encoded at the network coding sub-layer. The coding vectors are $g'_1, g'_2, \ldots, g'_s$: the elements of the generic vector g'_i ($i = 1, \ldots s$) are all zeros except for the i-th element, which is equal to one. The source neighbors that receive s encoded packets belonging to a given generation, can therefore decode the corresponding s native packets.

Intermediate node operations. Intermediate nodes perform re-encoding operations. When an intermediate node receives the first encoded packet of a given generation, i.e., its generation identifier differs from the one seen in earlier packets, the packet is cached in the NC buffer and a timer is started. The intermediate node then has to establish whether the subsequently received encoded packets belonging to the same generation are innovative. It thus applies the Gaussian elimination method and checks whether the rank of G increases when the new encoded packet is added to the buffer. If not, the packet is dropped, otherwise it is cached in the buffer. Therefore, an intermediate node only forwards one re-encoded packet following the reception of at most s encoded packets.

Destination node operations. The destination node can recover the set of native packets M_l, M_{l+1}, …, M_{l+v}. The receiver can also perform an early decoding when a G sub-matrix has full rank, i.e., when the sub-matrix rank is equal to v, with $v<s$. In this case, the receiver can recover v out of s source native packets belonging to the given generation.

We finally observe that when a node receives a packet, it must check whether it is innovative or not, i.e., whether it increases the rank of the decoding matrix G. If not, the packet is dropped.

4. Simulation Experiments

4.1 Simulation Model and Performance Metrics

To conduct the simulation studies, we have used randomly generated networks on which the algorithms were executed [21]. This ensures that the simulation results are independent of the characteristics of any particular network topology.

To effectively evaluate NCMR's performance, we compare it with other famous multipath routing protocols, AODVM [6], and MDSR [7] for cost to control information, average link-connect time, the success rate to find the path and the feature of data transmission.

A wireless sensor network is generated as follows: The Distributed Coordination Function (DCF) of IEEE 802.11 for wireless LANs is used as the MAC layer protocols. There are 100 nodes in the network and they are confined in a square area of 1000m × 1000m; WSN is modeled as a shared media radio with a nominal bit-rate of 2 Mbps and a nominal radio range of 250 meters. In the beginning, the nodes are randomly placed in the area. Each node remains stationary for a pause time, that is exponentially distributed with a mean of 600 seconds. We chose our traffic sources to be constant bit rate (CBR) source. When defining the parameters of communicationmode, we testedwith the packet sending rate 4 packets per seconds, and packet size of 64 bytes.

We will compare the performance of three multipath routing methods under the same movement models and communication models. We evaluate the performance according to the following metrics: packet delivery rate, average packet delivery delay, packet loss probability and network lifetime.

4.2 Simulation Results

To assess and compare the performance of the three broadcasting schemes discussed above, we implemented them in the network simulator ns-2 [22]. NS-2 is a discrete event simulator targeted at networking research. NS-2 provides substantial support for simulation of TCP, routing, and multipath protocols over wired and wireless networks.

In Fig. 2, NCMR demonstrates near 100% data delivery regardless of number of neighbors, block size, packet drop probability. On the other hand, the packet delivery ratio of the conventional multicasting represented by AODVM and MDSR degrades from 99% to 94% as number of neighbors and packet drop probability increase. The packet delivery ratio is defineud as the ratio of data packets received by all receivers over total data packets sent.

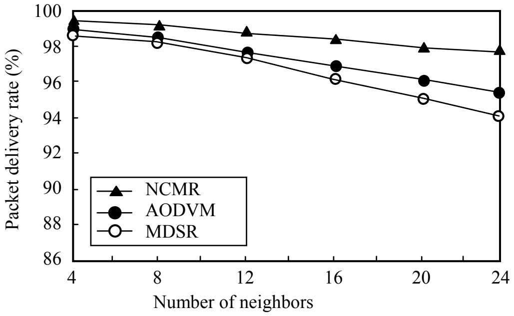

Fig. 2 Comparison of packet delivery rate.

We start by looking at the average value of the packet delivery delay, which is defined as the time elapsed from the time instant when the packet is generated at the source node to the time instant when the packet is received by a destination node. Fig. 3 shows that the average packet delivery delay has a decreasing trend as the number of neighbors increases. The reason for this behavior is that a wider radio range yields fewer hops, hence lower delay.

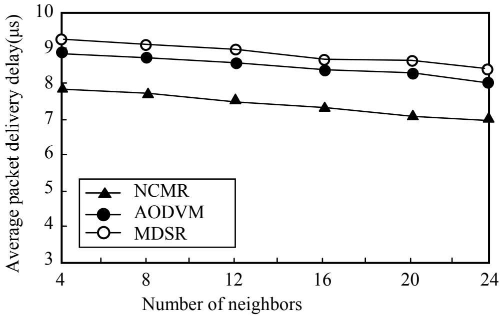

Fig. 3 Comparison of average packet delivery delay.

Next, we focus on the packet loss probability recorded at the application layer. As shown in the top plot of Fig. 4, the packet loss probability in the random topology case decreases as the neighborhood size increases. Indeed, as the network becomes more and more connected, nodes can receive packets from different neighbors thus having more chance to receive all broadcast packets. NCMR transmits packets through multiple paths to take advantage of paths redundancy and reduces the number of lost packets provoked by selfish nodes. However, NCMR uses the network coding and includes data in transmission packets. this approach seems convenient because it reduces the packet loss rate, it is not scalable and the performances will certainly collapse if the number of transmissions increases.

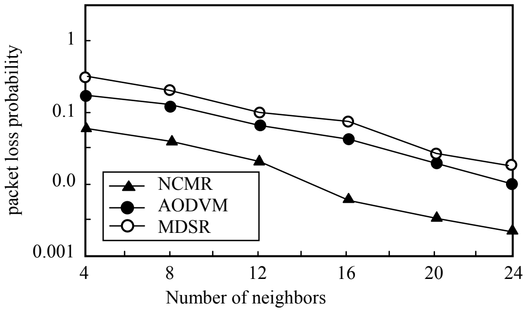

Fig. 4 Comparison of packet loss probability.

Fig. 5 shows that the network lifetime has a decreasing trend as the mobility speed increases. Under all the max speeds, NC-MR gives much longer lifetime than FZR and ENDMR approach. NC-MR get nearly lifetime 10-20% higher than FZR and ENDMR. We can also observe that the network lifetime with multipath routing degrades more gracefully than other routing protocols when the nodes' mobility speed increases. It demonstrates that our routing scheme is more stable with the variation of the nodes' mobility speed.

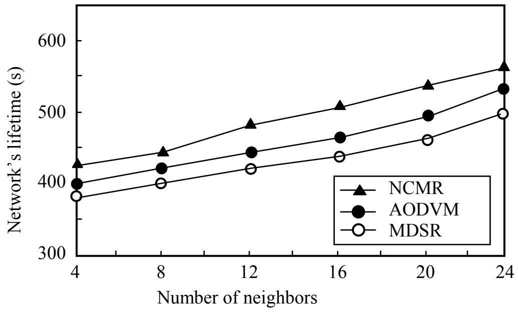

Fig. 5 Comparison of network's lifetime.

5. Conclusions and Future Work

This paper discusses multpath routing problem, which may deal with the network coding model for researching the WSN multpath routing problem. It presents proposes a Network Coding in WSN multipath routing protocol. It is typically proposed in order to increase the reliability of data transmission, and by applying network coding, which allows packet encoding at a relay node. we compare the performance of different protocols for WSNs - AODVM and MDSR routing protocol. Simulation results show that, with the proposed network coding in WSN multipath routing protocol (NCMR), packet delivery rate, average packet delivery delay, packet loss probability and network lifetime can be improved in most of cases.

In terms of future work, we would definitely consider optimizing the timeout values and other parameters used in NC-MR for further evaluation via simulation. Use of the node-disjoint paths in parallel to improve the QoS performance and increase the network utilization, is left as our future work.

Acknowledgments

This work is supported by The Young and Middle-aged Elitists' Scientific and Technological Innovation Team Project of the Institutions of Higher Education in Hubei Province (No. T200902), Natural Science Foundation of Hubei Province of China (No. 2010CDB05601), Key Scientific Research Project of Hubei Education Department (No. D20121903, Q20112205, Q20111610, and Q20121906).

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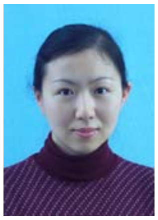

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