An Efficient Network-Wide Reliable Broadcast Protocol for Medical Sensor Networks

Xinguo Wang, Run Hu(✉), Lutao Wang, Dongrui Gao, Yuyuan Su, and Bin Yang

Chengdu University of Information Technology, Chengdu 610225, People's Republic of China
{wxg,wanglt,gdr1987}@cuit.edu.cn, seeinghr@163.com,
774816068@qq.com, 763215080@qq.com

Abstract. Medical sensor networks provide rich contextual information and alerting mechanisms with continuous monitoring. Broadcast is an important communication mode for medical sensor networks. Most existing broadcast protocols for wireless sensor networks use a minimal virtual backbone subnetwork to broadcast packets, which can minimize the total number of transmissions. However, since the unreliability of wireless link is not considered, the broadcast efficiency of these protocols is not high in factual networks. This paper proposes an efficient networkwide reliable broadcast protocol (ENWRB), which adopts network coding scheme to reduce the retransmissions in single-hop broadcast and a link quality-aware virtual backbone election algorithm to generate the more efficient broadcast backbone. Simulation results show that, under the same premise of ensuring all nodes receive broadcast packets successfully, the efficiency of ENWRB is higher than that of Hierarchical CDS-based Algorithm (HCA) greatly.

Keywords: Network-wide reliable broadcast · Medical sensor networks · Virtual backbone · Network coding

1 Introduction

The combination of wireless sensors and sensor networks with computing and artificial intelligence research has built a cross-disciplinary concept of ambient intelligence in order to overcome the challenges we face in everyday life. Wearable and implantable body sensor network systems [1] allow people to be monitored during all their everyday activities. Medical sensor networks [2] can help people by providing healthcare services such as medical monitoring, memory enhancement, control of home appliances, medical data access, and communication in emergency situations. Constant monitoring will increase early detection of emergency conditions and diseases for at risk patients and also provide wide range of healthcare services for people with various degrees of cognitive and physical disabilities. Network-wide broadcasting, is an important communication mode in medical sensor networks, where the packets originate from any node need to be delivered to the other nodes. It can be widely utilized by various of network services, such as notification, paging, routing discovery and etc. A network-wide broadcast protocol must ensure that all nodes can receive broadcast packets correctly, which means

L. Peñalver and L. Parra (Eds.): Industrial IoT 2020, LNICST 365, pp. 34–44, 2021.
https://doi.org/10.1007/978-3-030-71061-3_3

that the whole network needs to be covered fully, and the total number of transmissions should be reduced as much as possible to improve the broadcasting efficiency.

At this stage, there is a rich body of researches on network-wide broadcasting protocols [3–9], these can be roughly divided into the following three categories, namely network flooding, probability-based forwarding, backbone-based forwarding and so on [10]. In network flooding protocols, all nodes participate in forwarding broadcast packets, which can achieve full network coverage with very high probability at the cost of introducing too many redundant transmissions. In probability-based forwarding, each node is assigned a probability of participating in packet forwarding. Although it can reduce the number of transmissions, it is difficult to guarantee the full coverage by selecting an appropriate forwarding probability. In backbone-based forwarding, a connected subnetwork is established, where each node is either a backbone node, or has at least one back-bone neighbor. When the nodes in the backbone subnetwork participate in forwarding broadcast packets, all the other nodes can be covered fully.

Obviously, the smaller the size of such a virtual backbone network, the fewer the total transmissions and so the higher the broadcast efficiency. Therefore, the existing studies mainly focus on how to generate the smallest virtual backbone network. In [11], the authors have already proved that generating the smallest virtual backbone even with the global topology information is a NP (Non-deterministic Polynomial) - hard problem. The subsequent studies are committed to approximate optimal algorithms instead. Moreover, it is costly to obtain the global topology knowledge in large-scale medical sensor networks. In [12], the authors proposed a distributed backbone election algorithm only based on the local topology information.

However, these works all assume that the wireless links are reliable. In factual networks, due to the ubiquitous link errors, there will be a large of retransmissions in order to achieve really full coverage. We argue that broadcast forwarding based on the smallest virtual backbone cannot minimize the total number of transmissions any more. In this paper, our contributions are twofold. Firstly, we introduce the network coding technique into the retransmitting procedure and reduce the transmissions of single-hop broadcasting greatly through a greedy coding scheme. Secondly, we analyze how many transmissions are needed for each node to deliver the broadcasting packet to all of its neighbors successfully. Finally, this new metric is used in a distributed backbone election algorithm, where the node with a small metric value is preferred to be elected as a backbone node. Extensive simulation results show that the proposed network-wide broadcasting protocol can reduce the total number of transmissions greatly.

The rest of this paper is organized as follows. Section 2 studies how to use network-coding to reduce the retransmissions of the single-hop reliable broadcasting. Section 3 analyzes the performance gain achieved by network-coding. Section 4 proposes the backbone-based network-wide broadcasting protocol formally. Section 5 presents the simulation results. In final, Sect. 6 concludes this paper and discusses the future research direction.

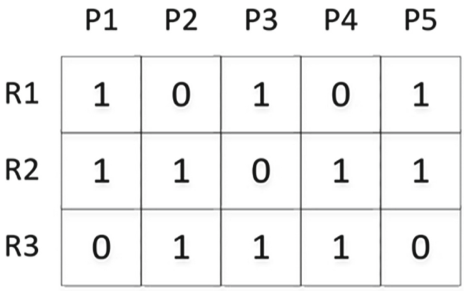
2 Single-Hop Broadcast

In this section, we consider the single-hop reliable broadcast problem for medical sensor networks, where a sender s needs to reliably deliver M pieces of packets to N direct neighbors, which are denoted by $R = \{R_1, R_2, \ldots, R_N\}$. In traditional protocols, sender s has to retransmit each packet until all neighbors have acknowledged that they have received it successfully. It is costly to complete reliable broadcast delivery through such a stupid retransmission mechanism.

Since the link states are independent of each other, different neighbors may request sender s to retransmit the different packets, resulting in too many retransmissions. If these packets have the same length, sender s can encode multiple packets asked by different neighbors into one packet and only retransmit the coded one. Combined with the previously received packets, each neighbor can recover one original packet from the coded packet. By utilizing this gain, network coding can reduce the number of retransmissions and improve the broadcast efficiency greatly. The more packets encoded, the more gain achieved [13].

Specifically, each sender uses an acknowledgement matrix $A_{N \times M}$, to record the reception status of N neighbors about M packets. If neighbor i has acknowledged the successful reception of packet j, $a_{i,j}$ is equal to 1. Otherwise, $a_{i,j}$ is equal to 0. Senders uses XOR coding to encode $m(m \leq M)$ packets $P_1, P_2, \ldots, P_m$ into one packet $\oplus(P_1, P_2, \ldots, P_m)$, which is equal to $P_1 \oplus P_2 \cdots \oplus P_m$. A neighbor can recover the missing packet by using $\oplus(P_1, P_2, \ldots, P_m)$ to execute XOR operation with the previously received $m - 1$ packets serially.

As shown in Fig. 1, five packets need to be delivered to all three neighbors. For the convenience of analysis, we assume that there is no retransmission error. If no coding is applied, five transmissions are needed since all five packets are asked by at least one neighbor. If coding is applied, sender s needs to retransmit $\oplus(P_1, P_2)$, $\oplus(P_3, P_4)$, and P_5, sum to three transmissions. Thus, network coding can reduce the total transmissions of a reliable single-hop broadcasting.



	P1	P2	P3	P4	P5
R1	1	0	1	0	1
R2	1	1	0	1	1
R3	0	1	1	1	0

Fig. 1. Reception status matrix for reliable broadcast

In fact, there is a better coding solution for the scenario in Fig. 1. Sender s only needs to retransmit $\oplus(P_1, P_2, P_3)$ and $\oplus(P_4, P_5)$, where two transmissions are enough. The authors in [14] have already proved that finding the best coding solution based on reception matrix is also a NP-hard problem. Due to the limitation of XOR coding, sender s cannot encode multiple original packets that are requested by the same neighbor into one packet. Otherwise, this neighbor cannot decode it. In addition, an original packet that is requested by more neighbors helps to obtain a larger coding gain. Here, we propose the following heuristic coding algorithm based on greedy strategy.

Algorithm 1 The coding algorithm based on greedy strategy

```
 1: Step1: $S \leftarrow \Phi, C \leftarrow \Phi$
 2: Step2: Execute the following sub-operations circularly until (1) can't find any eligible packet
 3: (1) find the packet $p_i$ based on the following rules:
 4:     a) exclude the packets asked by any neighbor in $S$
 5:     b) maximize the number of neighbors that needs $p_i$
 6:     c) minimize $i$, the index of $p_i$, based on a) and b)
 7: (2) add $p_i$ into set $C$
 8: (3) add all the neighbors that request to retransmit $p_i$ into set $S$
 9: (4) set column $i$ of matrix $A$ to be all-one
10: Step3: encode all the packets in $C$ into a new packet $p_j$
```

Algorithm 1 describes the process of encoding multiple original packets into the one packet. C denotes the set of original packets to be encoded and S denotes the set of neighbors that can decode the packet successfully. In line 1, these two sets are both initialized to be empty. From line 3 to line 6, picks out the packet that is not requested by any neighbor already in S and has the largest coding gain by far. In line 7 and line 8, p_i and the neighbors that request retransmit p_i are added into C and S, respectively. Then, the reception matrix is updated. These operations are executed circularly until there is no longer any eligible packet. Finally, all the packets in C are encoded into one packet. This packet becomes a new original packet and only needs to be delivered to a subset of N neighbors.

3 Network Coding Gain

In this section, we analyze the gain brought by network coding. We assume that the packet error ratios between sender s and N neighbors are $e_1, e_2, \ldots, e_N$, respectively. Without network coding, sender s needs to retransmit an original packet once any neighbor fails to receive it. For a generic link, if sender s transmits k packets, the probability that neighbor i can receive one or more packets is equal to$1 - e_i^k$. Due to the independency of link states, the probability that N neighbors all receive at least one packet from k packets are given by $\prod_{i=1}^{N}(1 - e_i^k)$. Next, the probability that sender s needs to transmit k packets to ensure that all N neighbors receive at least one packet can be calculated as $\prod_{i=1}^{N}(1 - e_i^k) - \prod_{i=1}^{N}(1 - e_i^{k-1})$. In final, we can get the expected value of the total number of transmissions to guarantee all N neighbors to receive M original packets, which is given by the following expression,

$$T_x(N, M) = M \sum_{k=1}^{\infty} k \left(\prod_{i=1}^{N} \left(1 - e_i^k\right) - \prod_{i=1}^{N} \left(1 - e_i^{k-1}\right) \right) \quad (1)$$

$$= M \sum_{l_1, l_2, \ldots, l_N} \frac{(-1)^{\left(\sum_{i=1}^{N} l_i\right) - 1}}{1 - \prod_{i=1}^{N} \left(e_i^{l_i}\right)} \quad (2)$$

where l_i is a binary variable and $\sum_{i=1}^{N} l_i > 0$.

Next, we analyze how many transmissions needed by a single-hop reliable broadcast when applying network coding mechanism. Without loss of generality, we assume that $e_1 \leq e_2 \cdots \leq e_N$ and $\sum_{i=1}^{N} e_i \leq 1$.

Theorem 1. The minimal number of coded packets needed by delivering M original packets to N neighbors successfully is equal to M_{e_N}.

Proof. The proof is straightforward. Since each neighbor can recover only one original packet from a coded packet, the neighbor whose link error ratio is e_N needs to at least receive M_{e_N} coded packets to recover all M original packets.

Theorem 2. If the condition $\sum_{i=1}^{N} e_i < 1$ is satisfied, N neighbors all can recover M original packets after receiving M_{e_N} coded packets successfully.

Proof. If $\sum_{i=1}^{N} a_{i,j} \geq N - 1$ for ∀j the coding algorithm will select one original packet for all the neighbors in R $- \{r_i | \sum_{j=1}^{M} a_{i,j} = M\}$. Then, N neighbors can recover all M original packets after receiving M_{e_N} coded packets. Otherwise, without loss of generality, assume $\exists j^{'}$, $\sum_{i=1}^{N} a_{i,j^{'}} < N - 1$ and ∀j $\neq j^{'}$, $\sum_{i=1}^{N} a_{i,j} \geq N - 1$. Since $\sum_{i=1}^{N} e_i \leq 1$, $A_{N \times M}$ has $N - 1 - \sum_{i=1}^{N} a_{i,j}$ all-one columns so far. Therefore, N neighbors all can recover M original packets after receiving M_{e_N} coded packets successfully.

Sender s first broadcasts M original packets. Then, Algorithm 1 will select one missing packet for each neighbor who have not received all M packets at each round. All M_{e_N} coded packets can be divided into N batches according to the number of neighbors that can recover some packet. The numbers of these batches are $M_{e_1}, M_{(e_2-e_1)}, \ldots, M_{(e_N-e_{N-1})}$. Since the first M_{e_1} coded packets are delivered to N neighbors, the expected number of transmissions is $T_x(N, M_{e_1})$. The second $M_{(e_1-e_2)}$ coded packets are only delivered to $N - 1$ neighbors, and the expected number of transmissions is $T_x(N - 1, M_{(e_2-e_1)})$. Likewise, the final $M_{(e_N-e_{N-1})}$ coded packets are only delivered to 1 neighbor and the expected number of transmissions is $T_x(1, M_{(e_N-e_{N-1})})$. Therefore, the total number of transmissions of a single-hop broadcast using network coding can be estimated as the following expressions,

$$T_X^{NC}(N, M) = M + \sum_{i=1}^{N} T_X(i, M(e_{N+1-i} - e_{N-i})) \tag{3}$$

4 Network-Wide Broadcast

In network-wide broadcast, packet needs to be delivered to all the nodes of the whole network. When taking transmission errors into account, the optimization goal of back-bone based network-wide broadcast is no longer to minimize the number of virtual backbone nodes, but to minimize the total number of transmissions. In this section, we will propose an efficient network-wide reliable broadcast (ENWRB) protocol based on network coding and backbone network, which can reduce the total number of transmissions greatly.

Like the other distributed backbone election algorithms [15], ENWRB protocol is divided into an initial phase and a pruning phase. In the initial phase, a backbone network with high connectivity is constructed according to the 2-hop neighbor information. In the pruning phase, unnecessary nodes with low broadcast efficiency will be deleted from the initial backbone network. For description convenience, we denote the set of 1-hop neighbor nodes of node u by $N(u)$.

In the initial phase, each node broadcasts *HELLO* packets, which includes *ID* information of itself and its 1-hop neighbors. If node u has two neighbors, for nodes v and w example, which are not adjacent to each other, it indicates that v and w may need to forward packets through u. Thus, node u becomes the initial backbone node. It is obvious that this mechanism can generate a backbone subnetwork. As shown in Fig. 2, nodes b, c, f and h form the initial backbone. However, there are many redundant backbone nodes, which will reduce the efficiency of network-wide broadcast.

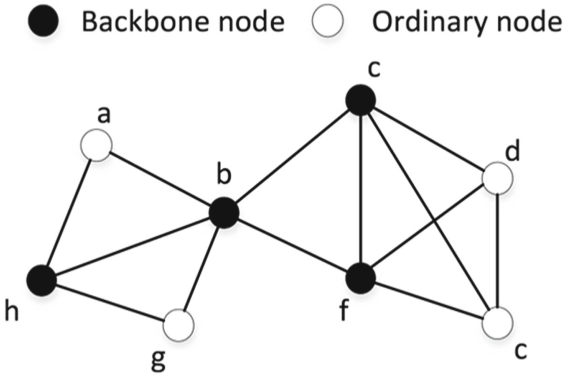


Fig. 2. Initial virtual backbone network

In the second phase, each backbone node elected in the initial phase will decide to whether be a final backbone node or not according to 2-hop topology information and the efficiency as a broadcast backbone, which is defined by the following expression,

$$\eta = \frac{N \times M}{T_X^{NC}(N.M)} \tag{4}$$

The larger the η value, the higher the priority of being a final backbone node. Thus, ENWRB protocol prefers to choose the nodes with high node degrees and good links. The packet error ratios can be obtained through counting the correct reception ratio or signal strength of the periodical *HELLO* packets. A generic backbone node u decides to whether be a final backbone node according to the following rules,

a. If there is another initial backbone node v, which can cover all the 1-hop neighbors of node u, (namely $N(u) - \{v\} \subset N(v)$), and the priority of node v is higher than u, then u will quit the election of backbone node.

b. If there are another two initial backbone nodes v and w, which are adjacent to each other and they can cover all the 1-hop neighbors of node u cooperatively, (namely $N(u) - \{v; w\} \subset N(v) \cup N(w)$), and the priorities of nodes v and w are higher than u, then u will quit the election of backbone node.

As shown in Fig. 3, the high packet error ratio between node c and d leads to a low broadcast efficiency of node c, and so node c will not become the final backbone node. In the protocol proposed in [15], node h will not become a backbone node, but h will become a backbone node in our protocol, which can avoid a large number of retransmissions due to the worse link between node b to g. Therefore, nodes b, f, and h constitute the final virtual backbone subnetwork. The link layer protocol usually sends *HELLO* packets and contains the information needed by generating the virtual backbone network, so the proposed mechanism does not introduce an extra overhead. In fact, multiple backbone nodes that cover the same ordinary node redundantly can cooperate with each other by overhearing the broadcast progress of each other, which can help reduce the total number of transmissions further.

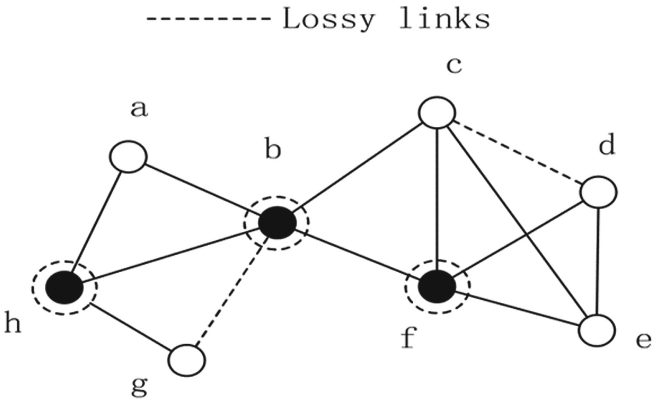


Fig. 3. Final virtual backbone network

5 Simulation Results

In this section, we evaluate the performance of proposed protocol. Firstly, we compare the number of transmissions of reliable single-hop broadcast with or without network coding on the MATLAB platform. The number of neighbors is set as 20 and 10, while the number of original packets is set as 100 and 50, respectively. The packet error ratio of each wire-less link is randomly generated [16, 17], where the minimal ratio is equal to 0 and the maximal ratio ranges from 0.01 to 0.05. The results shown in Fig. 4 are the average values of 100 simulations. In general, the total transmissions increase with the number of neighbors and the number of original packets, and the results with network coding is much less than without network coding. For example, when N = 20, M = 100, and the maximal packet error ratio is equal to 0.05, the total number of transmissions

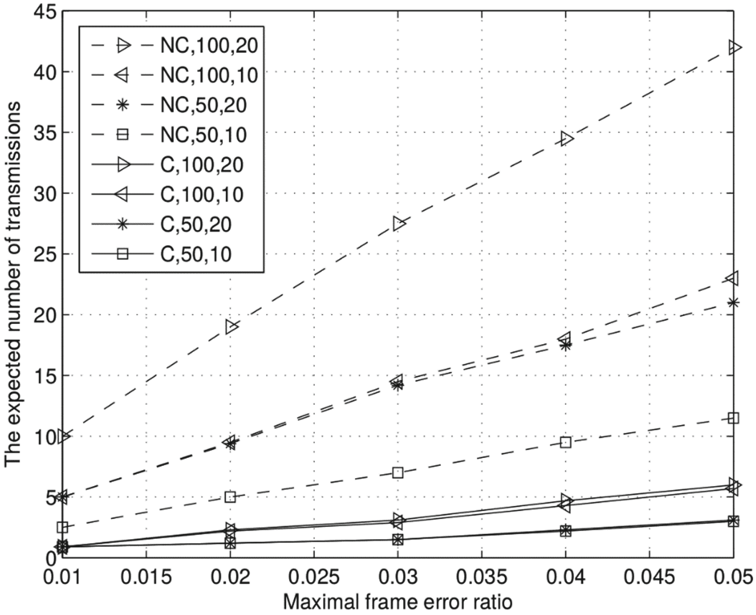


Fig. 4. Expected number of transmissions for single-hop broadcast

without network coding is approximately equal to 42.7, meanwhile the total number with network coding is approximately equal to 7.3.

Next, we compare the performance of ENWRB protocol with HCA (Hierarchical CDS-based Algorithm) proposed in [12], in terms of the size of backbone subnetwork and the total number of transmissions of network-wide broadcast. We implement these two protocols based on NS (Network Simulation) platform. For the sake of fairness, it is assumed that HCA also adopts the single-hop broadcast mechanism based on network coding to reduce the number of transmissions of single-hop broadcast. All nodes are distributed randomly within a square area, where the length is 200 m. The communication radius of each node is equal to 50 m. The maximum packet error ratio of the link is 0.05, and M is set to 100. The source nodes of broadcasting packets are randomly generated and all the original packets have the same length. The forwarding nodes can distinguish these packets according to the ID of source node and the unique sequence number of packets.

The numbers of backbone nodes are given in Fig. 5. We can see that ENWRB generates a slightly larger backbone sub-network than HCA generally in order to achieve higher broadcast efficiency. This phenomenon is more obvious in networks with lower node densities. The total numbers of transmissions of broadcasting an original packet to all nodes in the entire network are shown in Fig. 6, where each point is the average value of 10000 original packets. In general, the efficiency of ENWRB is higher than HCA, since its total number of transmissions is less than HCA. Such an advantage increases with the network density. When the number of network nodes increases to 200, the total number of transmissions of ENWRB is only about 72% of HCA.

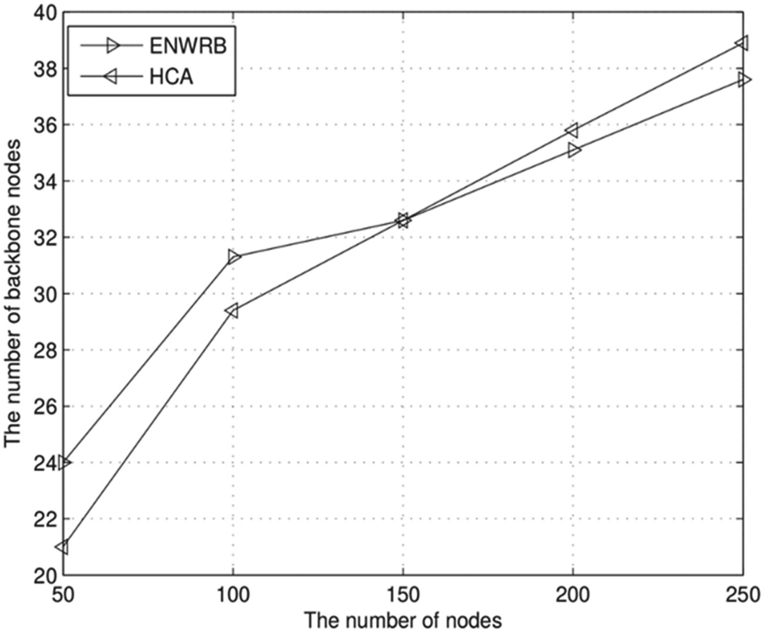


Fig. 5. Number of backbone nodes for network-wide broadcast

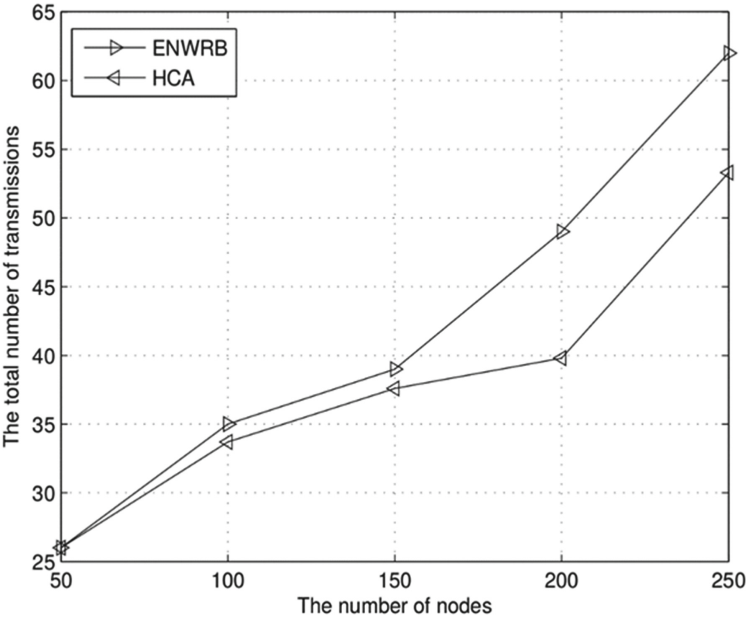


Fig. 6. Total number of transmissions for network-wide broadcast

6 Conclusion

In this paper, we study the network-wide reliable broadcast problem. Firstly, network coding is used in the single-hop broadcast to reduce the number of retransmissions. Meanwhile, the corresponding gain brought by network coding is analyzed. Then, based on the single-hop broadcast mechanism, a network-wide reliable broadcast protocol based on virtual backbone network is proposed to reduce the total number of transmissions across the network. The simulation results show that ENWRB has higher broadcasting efficiency than HCA, under the premise that all nodes in the whole network should receive broadcast packets correctly. Due to the network coding mechanism may increase the time of completing the broadcast of the whole network, so in our future works, we will take some measures to decrease the delay of ENWRB effectively and efficiently.

Acknowledgments. This paper is supported by Sichuan Science and Technology Program under 2019YFG0196 and 2020YFG0442.

References

1. Movassaghi, S., Abolhasan, M., Lipman, J., Smith, D., Jamalipour, A.: Wireless body area networks: a survey. IEEE Commun. Surv. Tutorials **16**(3), 1658–1686 (2014) Third Quarter
2. Ko, J., Lu, C., Srivastava, M.B., Stankovic, J.A., Terzis, A., Welsh, M.: Wireless sensor networks for healthcare. In: Proceedings of the IEEE, vol. 98, no. 11, pp. 1947–1960, November 2010
3. Tavli, B., Heinzelman, W.B.: Energy and spatial reuse efficient network-wide real-time data broadcasting in mobile ad hoc networks. IEEE Trans. Mobile Comput. **5**(10), 1297–1312 (2006)
4. Hurni, P., Braun, T.: An energy-efficient broadcasting scheme for unsynchronized wireless sensor MAC protocols. In: 2010 Seventh International Conference on Wireless On-demand Network Systems and Services (WONS), Kranjska Gora, pp. 39–46 (2010)
5. Lichtblau, B., Redlich, J.: Network-wide broadcasts for wireless mesh networks with regard to reliability. In: 2012 19th IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT), Eindhoven, pp. 1–6 (2012)
6. Lichtblau, B., Dittrich, A.: Probabilistic breadth-first search - a method for evaluation of network-wide broadcast protocols. In: 2014 6th International Conference on New Technologies, Mobility and Security (NTMS), Dubai, pp. 1–6 (2014)
7. Zhang, X., Yan, F., Li, C., Ding, Q.: Coverage efficiency-based broadcast protocol for asynchronous wireless sensor networks. IEEE Wirel. Commun. Lett. **5**(1), 76–79 (2016)
8. Zhang, X., Jia, X., Yan, F.: Dynamic delegation-based efficient broadcast protocol for asynchronous wireless sensor networks. IEEE Commun. Lett. **20**(6), 1195–1198 (2016)
9. Wang, X., Wu, X., Zhang, X., Liang, Y.: An energy-efficient network-wide broadcast protocol for asynchronous wireless sensor networks. IEEE Wirel. Commun. Lett. **7**(6), 918–921 (2018)
10. Wisitpongphan, N., Tonguz, O.K., Parikh, J.S., Mudalige, P., Bai, F., Sadekar, V.: Broadcast storm mitigation techniques in vehicular ad hoc networks. IEEE Wirel. Commun. **14**(6), 84–96 (2007)
11. Hong, J., Cao, J., Li, W., Lu, S., Chen, D.: Minimum-transmission broadcast in uncoordinated duty-cycled wireless ad hoc networks. IEEE Trans. Veh. Technol. **59**(1), 307–318 (2010)

12. Tang, B., Ye, B., Hong, J., You, K., Lu, S.: Distributed low redundancy broadcast for uncoordinated duty-cycled WANETs. In: 2011 IEEE Global Telecommunications Conference, pp. 1–5. IEEE (2011)
13. Nguyen, D., Tran, T., Nguyen, T., Bose, B.: Wireless broadcast using network coding. IEEE Trans. Veh. Technol. **58**(2), 914–925 (2009)
14. Chi, K., Jiang, X., Ye, B., Horiguchi, S.: Efficient network coding-based loss recovery for reliable multicast in wireless networks. IEICE Trans. Commun. **E93.B**(4), 971–981 (2010)
15. Dai, F., Wu, J.: An extended localized algorithm for connected dominating set formation in ad hoc wireless networks. IEEE Trans. Parallel Distrib. Syst. **15**(10), 908–920 (2004)
16. Basagni, S., Mastrogiovanni, M., Panconesi, A., Petrioli, C.: Localized protocols for ad hoc clustering and backbone formation: a performance comparison. IEEE Trans. Parallel Distrib. Syst. **17**(4), 292–306 (2006)
17. Kumar, G., Kumar Rai, M.: An energy efficient and optimized load balanced localization method using CDS with one-hop neighbourhood and genetic algorithm in WSNs. J. Network Comput. Appl. **78**, 73–82 (2017)