A Joint Design of Deployment and Routing for Lifetime Maximization in Pipeline Sensor Networks

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2022 International Symposium on Networks, Computers and Communications (ISNCC) | 978-1-6654-8544-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/ISNCC55209.2022.9851806

Abstract—**Pipeline monitoring is of the essence for nowadays oil and natural gas delivery. Wireless Sensor Network (WSN) is the best candidate due to its low cost, ad-hoc feature, and ease of maintenance. However, there are quite limited WSNs that are particularly designed for long pipeline monitoring. Meanwhile, directly applying existing protocols may cause insufficient use of these WSNs and downgraded performance, especially on the lifetime of the network, which is a crucial metric for pipeline monitoring. Some efforts for lifetime extension do not fully utilize the features of pipeline or has some impractical assumptions when applying to pipeline scenarios. In this paper, we fully consider the practical factors and unique features of pipeline and propose a joint design of deployment and routing for such typed networks. In our design, a novel sensor deployment and a corresponding load balancing routing protocol are derived in terms of the maximized lifetime. The design considers the node damage, redundant data generated from the same event, and energy holes caused by dead nodes. Extensive simulation results validate our optimization and demonstrate our design can significantly improve the lifetime of the network and enjoy less overhead than the existing work. The simulation platform we used the MATLAB platform.**

Index Terms—**Long-Strip WSN, Midstream Pipeline, Lifetime Maximization**

I. Introduction

Pipeline monitoring (such as leaking, pollution, and compressor anomalies) is very important yet difficult to achieve, especially the pipeline for oil and natural gas delivery, due to its extraordinary long distance across uninhabited areas. While many technologies (e.g., drone, RF, WiFi, satellite, etc.) have been developed for monitoring systems, their prohibitively high installation complexity, short coverage range, and/or high energy consumption make them unsuitable for large-scale sensors in long-distance monitoring systems. On the other hand, wireless sensor networks (WSNs) have been rapidly developed and widely adopted in many monitoring application scenarios due to its large-scale and self-organized feature [1]. Various WSN protocols are designed for different purposes, such as short delay and high throughput [2], [3], desired QoS [4], topology control [5], and priority-based transmission [6].

However, WSNs particularly designed for pipeline monitoring are still less investigated, especially the design to prolong the lifetime of battery powered sensors, which cannot be easily replaced in the aforementioned environment. It is also inappropriate or will have downgraded performance to directly apply those well known lifetime extension protocols to pipeline network: 1) sensors with energy harvesting technique [7] can avoid battery replacement and thus can have the theoretically unlimited lifetime. However, existing techniques are mainly drove by sunlight, water wave, or RF collection. It can be hardly applied to the pipeline burying into the ground and crossing places without base station; 2) some efforts focused on the transmit power control [8], [9]. this kind of heterogeneous energy allocation strategy may be inconvenient in node manufacture and often assumes nodes can share their power info with no extra energy/overhead cost; and 3) some design addressed it by sensor deployment [10]–[13], but the system model and topology are often not matched with the pipeline system, such as multiple sinks in [10], [13], heterogeneous sensors in [11], sink mobility in [12], and three-dimensional coronary topology in [13].

Nevertheless, there are quite a few papers focused on maximizing the WSN for the pipeline sensing system. However, they have shortcomings of impractical assumptions or neglecting certain scenarios: *i)* [14] assumed all sensor nodes have capabilities to communicate with the sink directly; *ii)* [15] used the star topology other than the ad-hoc for their network, while most of the time there is no access point or base station for sensors; *iii)* [16] supposed there are multiple sinks in the network; *iv)* [17] considered the optimal node distance based on the transmission power but neglect the sensing coverage issue (further discussed in Sec. III-A); *v)* [18], [19] tried to save the energy by optimizing routing, but the performance has large randomness with different node topology. On the other hand, the optimized routing itself add biased load to particular nodes which expedite its energy consumption.

Moreover, the lifetime termed in most papers simply means the lifetime of a single node [14], not the lifetime of the entire network, and less considering the relationship between them. Another issue existed in above papers, more or less, is the neglecting of the energy consumed for the network overhead, including passive listening, advertising, message exchange for the real time local or global parameters, and the collision and retransmission (especially when trying to deploy more nodes to extend a single node's lifetime).

In this paper, we proposed JDR, a Joint design of nodes Deployment and energy-aware Routing strategy which fully considered practical factors and unique features of the pipeline sensor network in order to maximize the entire lifetime of the network, i.e., no need to replace the node when a single sensor

This work was supported in part by the US National Science Foundation (NSF) under Grant No. CCSS-2025307 and Lamar University Center for Midstream Management and Science (CMMS) Project 315.

978-1-6654-8544-9/22/$31.00 ©2022 IEEE

dead or not working. The routing protocol is customized to adapt with the deployment and an optimal deploying parameter is also proposed based on an analytical model. The validity of the model has been validated and the design is working well in degraded scenarios. More specifically, the salient features of JDR are summarized as follows:

1) To the best of our knowledge, JDR is the first network-based deployment design for lifetime prolonging in pipeline sensor network, which also considers node damage, function failures, redundant data, and energy holes.
2) The routing in JDR requires much less overhead (advertising, message exchange, and retransmission) than existing routing strategies.
3) The optimization is purely sensor based, which doesn't rely on any impractical assumptions or environmental parameters, such as the length of the pipeline. In other words, once sensors are chosen, the optimal parameter can be determined.
4) The linear ripple feature assist JDR to be easily integrated into existing and future design of linear sensor placement, or long strip sensor networks.

The rest of this paper is organized as follows. The system model and the problem formed in this paper are introduced in Section II. In Section III, we propose the deployment design with the customized routing, as well as the optimal parameter derivation. Model validation and performance comparison are analyzed in Section IV, followed by conclusions in Section V.

II. Problem Statement

A. Network Model

Pipeline monitoring sensor networks are made up of N sensor nodes and a sink. Considering a set of nodes deployed in a long strip sensing area. The sink is placed at the right end of the pipeline, as illustrated in Fig. 1. We assume the sensor network has the following properties:

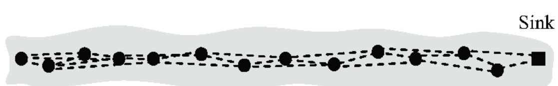


Fig. 1. A typical pipeline sensor network

1) Sensor nodes are responsible for collecting and preprocessing the monitoring information which will be sent to the sink for further analyzing, such that the destination of every sensing data is the sink.
2) Each node has a maximum transmission range noted as R_t. Each node has a maximum sensing range R_s for event detecting, such as abnormal pressure, high temperature, or air pollution.
3) The network runs with ad-hoc mode. The sensor transmits the data to its next hop node for relaying data to the sink. The connectivity problem in this paper is directly solved in the deploying phase.
4) When sensors are close enough, they will generate redundant data for the same event.
5) A sensor is claimed as 'dead' when it is unable to forward any packet back or forth. Thus, a dead sensor becomes an isolated node in the routing map.

It is worth to note that there are **no** assumptions on:

1) Physical location-awareness;
2) Distance estimation among nodes;
3) Transmit power control or adjustment.

B. Performance Metric

Before the problem statement is given, the definition of network lifetime for pipeline monitoring sensor networks is first introduced. In this paper, the time is divided into rounds as it has been done in most of previous studies [20]. Exactly in each round, every sensor node generates one data packet and send it together with other received packet to the next hop. Due to the nodes redundancy, if a node dies while its neighbors can: 1) detect the same event, and 2) perform the same rely function, the network still works. Hence, the lifetime definition is introduced as follows: the number of rounds when a certain amount of nodes are out of work, denoted as T, which causes the sink lack of sufficient information to monitor the overall state of the pipeline.

Based on [20], the expression of network lifetime in this paper is formulated as follows:

$$T = \frac{E_{MAX}}{\min(\Delta E(i))|_{i\in[1,m]}} \quad (1)$$

where E_{MAX} is the maximum energy stored in the sensor battery, $\Delta E(i)$ is the energy consumed by sensor i in each round, and m is the number of redundant nodes for an event area. Therefore, the denominator represents the energy consumption per round of the last dead node in a group of redundant nodes. When there are more redundant nodes (larger m), more chances to have a relatively less consumed node. On the other hand, more redundant nodes will cause more communication overhead (also related with the routing strategy) which increases the energy consumption of each node. Therefore, m is a tradeoff parameter needs to be optimized in our design.

Moreover, to make it clear, we also make the following assumptions regarding the monitoring networks.

1) Energy consumption mainly focuses on receiving and sending data packets, whereas power consumed for event sensing is negligible.
2) Neither conflict nor retransmission is considered during the data transmission process since time division multiplex and random backoff timer are adopted in our design.
3) The sensor price is not considered since most of time it is cheap unless the performance is close. Then, we will choose the deployment with fewer sensors.

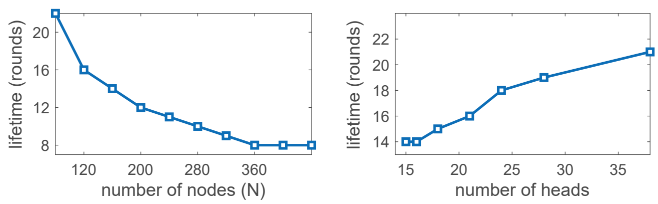
III. Proposed Joint Design

A. Factors Analysis

1) Dead Nodes Formation: Unlike existing works which simply attribute a sensor'death to the exhaustion of its power, we also consider the damage cost by natural and human factors. We use a damage probability p to represent the case that a node is dead but is not caused by power outage. The latter only needs to replace the battery but the prior needs to replace the sensor. Since this probability is unrelated with the energy consumption, it is reasonable to regard it as a memory-less factor, i.e., p maintains the same value in each round, which should be extremely small.

2) Energy Hole: When the monitoring scope is too large, nodes in different positions may deplete different amount of energy, which will lead to network energy load unbalanced. Some nodes tend to die out earlier than other nodes, resulting in what is called energy hole. When it happens, the network lifetime will drastically reduce and there is much more energy of nodes wasted after the monitoring networks are out of work. Combined with Eq. 1, we should make at least $m > 1$ in our design.

3) Number of Sensors: However, simply increasing m will not prolong the lifetime. We applied a practical clustering-based routing protocol (HCR) [19] to a pipeline scenario. As shown in Fig.2(a), when there are more nodes randomly deployed in the same area, indicating the number of redundant nodes (m) increased, however, the lifetime drastically decreased. This is because the cluster header carried more load on behalf of its members. This is further proved by Fig. 2(b). The lifetime increased when there are more cluster headers in the network, or, a more balanced load distribution. This motivates us to design a routing protocol that can evenly distributed the forwarding load.



(a) deployed more nodes (b) deployed more heads

Fig. 2. Observation of different deploying and routing strategies from HCR.

4) Nodes Placing Distance: As mentioned in the Introduction, authors often try to design an optimal distance between the linear placed sensors but neglecting the sensing coverage issue, i.e., the union of the area monitored by each sensor should fully cover the entire pipeline. In fact, we cannot do much about the interval distance since most of time $R_s << R_t$. To guarantee the sensing coverage, we should set $d = R_s$, which at the same time guarantees the connectivity of the network.

B. Nodes Deployment

In traditional WSNs on a flat area, sensors are often deployed in a ring structure to better incorporate with the cost field, as shown in Fig.3. Similarly, we evenly deploy m sensors onto equal distant (d) ring sections of a pipeline, as illustrated in Fig. 4. This topology generates two new salient features. First, when there is an unexpected event generated inside the pipeline, e.g., pressure anomalies, it radiates to the current section profile which can be detected by all m sensors on the ring. Moreover, unlike the flat case, every two sensors on adjacent pipe rings have similar interval since d is much greater than the pipe radius.

Each time when there is an event, the data will be first generated by the nearest ring, and then forwarded to the sink by each ring along the path, like a ripple in the pipeline. The ring close to the sink will receive ripples more often since events generated from various places will finally arrive here. Thus, it is more easily to generate energy holes here. *Nevertheless*, it can be easily mitigated by placing more sensors near sink [21] or just replace them more frequently since they are close to working place.

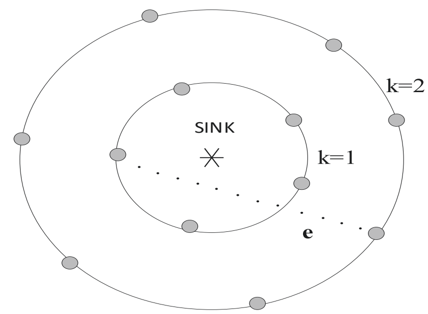


Fig. 3. An illustration of the flat deployment

C. Routing Protocol

From the conclusion drawn in Sec. III-A, we know it's better to evenly distribute the data load. Instead of choosing a dedicated relay node, we prefer some randomness on the next-hop selection. Therefore, *we expect the sensor on a ring can randomly choose another sensor on the next ring as its next hop*. To achieve this, one needs to know the nodes ID on its next ring towards the sink. This can be done during the cost field establishment, which is only operated once hence does not impact the complexity of the routing protocol, as explained in Alg. 1 and illustrated in Fig. 4. The hop count

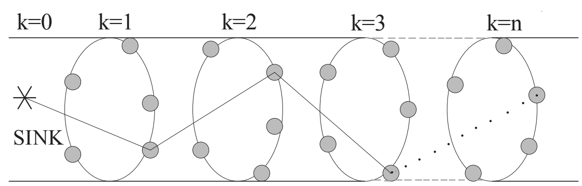


Fig. 4. An illustration of the routing process

Algorithm 1: Cost Field and Next-hop Set Establishment

Initial sensor'cost: $k_i = inf$;
if *Sink* **then**
    Broadcast ADV message ($k_{N+1} = 0$) at slot 0;
if *Sensor i receives an ADV message k_j* **then**
    if $k_j < k_i$ **then**
        $k_i = k_j + 1$;
        $\{i_{\text{nh}}\} \leftarrow j$;
        Broadcast ADV message (k_i) at slot k_i;

to the sink is used as the cost. The cost field is established by flooding the advertisement (ADV) message which contains the cost information k. The process of cost field establishment is divided into slots: at the beginning, the sink generates the ADV message including its cost $k = 0$, and then broadcast it in the range R_t at slot 0. The node received this ADV message reads the k and sets its cost k as 1. Then it will broadcast the ADV message with its cost $k = 1$ in R_t at slot 1. The nodes with the same cost k will broadcast ADV messages in the same slot, so the length of the slot should be set long enough to ensure that these nodes could have enough time to broadcast their ADV messages. This process repeats until all nodes have received ADV message and set their own cost. A node (i) may receive more than one ADV messages. In this case, the node compares their k. If they come from the node on the next ring towards the sink ($k = k_i - 1$), the node will add the ID to the set of its next hop candidates, $\{i_{\text{nh}}\}$. The node ignores all ADVs with ($k >= k_i$).

When there are dead nodes in the network, we call this degraded scenarios. We propose a mechanism to postpone the degraded case or work under the degraded case by further distributing the data based on receivers'energy levels. We ask each node to embed their residual energy information (E_R) in the ACK packet each time they send. Each time when a node overhears or receives an ACK, it stores the corresponding E_R if the sender is in its next hop set. Since the next hop is randomly chosen, a node has enough chances to receive all recent E_R information from all next hop candidates. Then, each time the node sends its data, it chooses a candidate in $\{i_{\text{nh}}\}$ with probability:

$$P(j) = \frac{E_R(j)}{\sum E_R|_{\{i_{\text{nh}}\}}} \tag{2}$$

When a node has less residual energy, it has less chance to be chosen by others as the next hop. In this way, the data load is balanced to those same-ring sensors with more energy and extend the appearance of energy hole.

When a node no longer receives ACK from a sensor, it exclude this sensor from its next hop list. In this way, the routing algorithm works even there are dead nodes. The selection and update algorithm is elaborated in Alg. 2, where t_b is the random backoff timer adopted in [22], [23] to schedule nodes sending sequence and avoid collision,

$$t_b = (K - k) \times T_{slot} + \left(\frac{E_{MAX} - E_R}{E_{MAX}}\right) \times T_{slot} \tag{3}$$

From the equation, the nodes on the farther ring will send first and node with less energy in a ring will send first. Thus, the data will be sent like ripples from the far-end to the sink.

The consumption can be further reduced by employing data fusion technique where each node preprocesses the received data and remove the redundancy [24]. It is especially useful and easy to use in our deployment since the data generated by same-ring nodes should be purely identical.

D. Optimal Ring Nodes

According to [25], a classical energy consumption model is proposed. In this model, the energy consumption for transmitting a 1-bit data packet over a distance R_t is

$$E_T = l \cdot E_{te} + l \cdot \epsilon_{amp} R_t^{\gamma} \tag{4}$$

The energy consumption for receiving/listening a l-bit data packet is

$$E_L = l \cdot E_{rx} \tag{5}$$

Algorithm 2: Next-hop Chosen and Set Update for S_i

Input: $\{i_{\text{nh}}\}$ and their E_R ;
1: Set up backoff Timer t_b ;
2: **while** $t_b > 0$ **do**
  if *receive DATA pkt* **then**
    data fusion ;
  if *overhear ACK pkt from sensor j* **then**
    update $E_R(j)$;
3: choose next hop t from $\{i_{\text{nh}}\}$ based on Eq. 2;
4: send data pkt ;
5: **if** *receive the ACK pkt* **then**
  update $E_R(t)$;
6: **else**
  remove t from $\{i_{\text{nh}}\}$;

Where E_{te} and E_{rx} denote the energy consumption per bit in transmitter and receiver circuit, respectively. ϵ accounts for the energy consumed in the transmit amplifier. γ denotes the path loss exponent, ranging from 2 to 4.

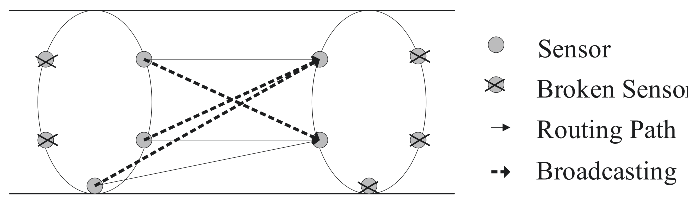


Fig. 5. A data transmission Scenario between two adjacent rings.

Next, based on our design, we will further derive the denominator in Eq. 1. Consider a data transmission scenario between two adjacent rings in Fig. 5 where $m = 5$. Each healthy node on the left ring will randomly select a node in the right ring as its next hop. At the same time, each healthy node in the right ring has averagely 1.5 data packets needs to forward. Meanwhile, each of them will overhear three transmissions from the left ring. This listening energy consumed is often neglected by other papers. Without loss of generality, we can assume the CSMA/CD is adopted by these nodes, i.e., only RTS message is overheard. In this case, a healthy node will overhear all RTS and CTS messages from all healthy nodes on its adjacent two rings. Suppose there are i nodes damaged in the left ring and j nodes damaged in the right ring. Consider the energy consumption of a healthy node on the right ring, which can represent the denominator in Eq. 1 since the energy consumed in each node should be quite similar under our design. We have

$$\Delta E(i,j) = 2(m-i) \cdot E_L \cdot size(\text{RTS+CTS}) + \frac{m-i}{m-j} \cdot E_T \tag{6}$$

Then, with the damage probability p (memory-less, as explained), we can further derive

$$\begin{aligned} \Delta E =&(1-p^m) \sum_i^{m-1} \sum_j^{m-1} \binom{m}{i} p^i (1-p)^{m-i} \\ &\cdot \binom{m}{j} p^j (1-p)^{m-j} \Delta E(i,j) + p^m E_{MAX} \end{aligned} \tag{7}$$

This is a convex function. A minimum ΔE exists with an optimal m. Regardless of γ and p which are constants when the monitoring environment is certain, we can see that the network lifetime T only has a close relationship with the data size, transmission range, and full battery energy, which are all sensor-related parameters. Thus, once sensors are chosen, the entire deployment can be determined.

IV. Performance Evaluation

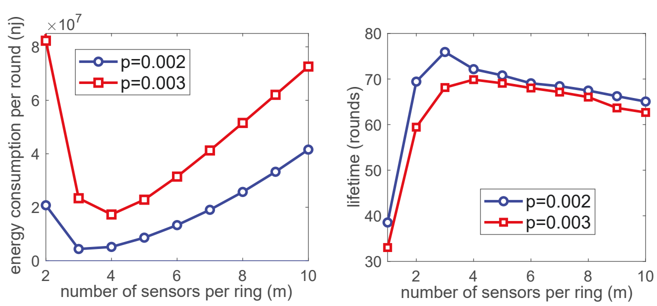
The performance of JDR protocol is evaluated in the following simulation scenario: nodes are deployed follow JDR over an area of size 3×400, and the sink resides at the middle of the right ends. The data transmission is scheduled by TDMA. The simulation parameters are similar to those in [19], which are summarized in Table I.

TABLE I
Simulation Parameters

Type	Parameter	Value
Application	Initial energy	2 J
	Maximum Tx range	40 m
	Data Packet Size	125 Bytes
	Time slot	20 TDM frames
Radio Model	E	50 nj/bit
	ϵ_{amp} in (4)	10 pj/bit/m^2
	γ in (4)	2

A. Optimization Validation

As shown in Fig.6(a), by our analytical calculation, when $m = 3$ with $p = 0.002$, the ΔE gets its minimum value. Meanwhile the simulation results in Fig.6(b) showed that the network gets its maximum lifetime when $m = 3$, which validates our model. Similarly, when $p = 0.003$, the optimal m derived by the analytical model also matched with the simulation results at 4. From the figures we can also realize that when p is larger, i.e., more risk to have a node damage, we need to deploy more redundant nodes per ring. Note that the p here corresponds to an approximate p^{25} probability (0.04-0.08) that represents a node will have an accidental damage before the battery exhausted, which satisfies natural cases.



(a) Analytical results (b) Simulation results

Fig. 6. Optimization Validation

B. Performance Comparison

The performance of JDR is compared with HCR over different number of nodes, as shown in Fig. 7. We compare HCR in two settings. One is where nodes randomly deployed. The other is using HCR with our deployment. For example, when N=30, it means $m = 3$ for JDR and JCR-grid deploy. From the figure we can see that JDR outperforms the two HCR settings significantly, almost tripled the lifetime. This is only considering the lifetime as one node dead, not to mention the lifetime defined in this paper. Moreover, the p is set to 0 for their simulation, which means the performance can be even downgraded for these design when considering the node damage factors. The HCR with our deployment seems have a better performance than randomly distributed nodes. However, the difference is negligible. That means simply adopting our design does not guarantee a better performance. It also proved that our joint design is organically correlated with each other, not just two separated design combined together.

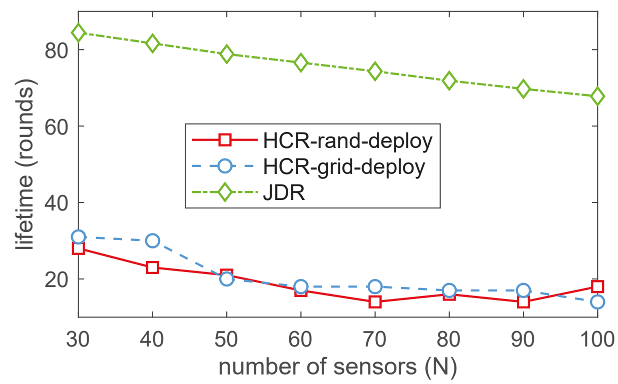


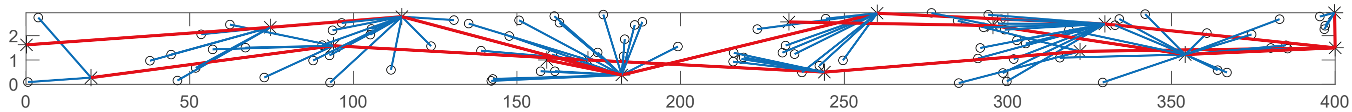
Fig. 7. Lifetime comparison

C. Routing Observation

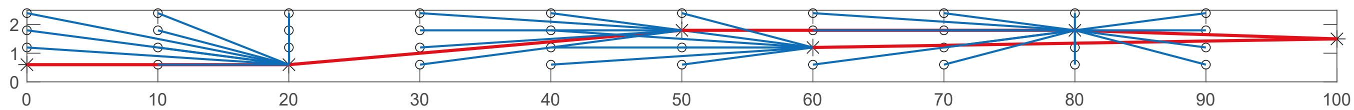
Fig. 8(a) illustrates the routing map of HCR with random nodes deployment. We can see the cluster is formed not reasonable enough when encountering with the pipeline topology. There are more than one cluster header paths existing. Also, the load is unbalanced between cluster members and cluster headers, even unbalanced between different cluster headers, which cause the energy of certain headers easily drained off and thus formed the energy hole.

Fig. 8(b) illustrates the routing map of HCR with our deployment. We can see the cluster is formed at a node of each ring. The routing path is more reasonable than the random one and the cluster headers have more balanced load. However, since they have destined routing hops. Whenever there is a damaged cluster header, the entire routing path is broken and the whole selection and routing process needs to be reperformed which consumes lots of energy and overhead. It is worth to mention that the entire set up process of JDR only needs one flooding from the sink. Therefore, JDR enjoys the least overhead.

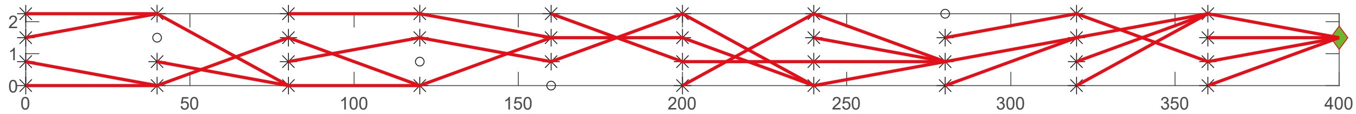
Fig. 8(c) illustrates the routing map of JDR. We can see that each node has a balanced routing load, i.e., every node has most of time only one path forwarded to it. If a node is dead (refer to circled nodes at x=40, x=120, and x=160), they became isolated nodes since our updating algorithm can avoid sensors to communicate with these dead nodes. The routing is still balanced with its best efforts based on the residual energy information. The network is thus well maintained until all nodes on a ring die.



(a) The routing map of HCR random distributed deployment



(b) The routing map of HCR grid distributed deployment



(c) The routing map of JDR

Fig. 8. Synchronous case and asynchronous cases in different designs.

V. Conclusion

In this paper, the unique feature and practical factors of pipeline sensing was investigated. A novel joint design of sensor deployment and routing is proposed. An important deployment parameter was modeled and optimized for the first time. The proposed model can be used under various conditions by taking into account the nodes damage, redundant data, and energy holes. Extensive simulations have been done for model validation and impact analysis. The proposed model has a potentially transformative value to be implemented into any long strip WSNs.

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