Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

7th International Conference
on Electrical Engineering
ICEENG 2010

Modeling Reliability in Wireless Sensor Networks

By

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Abstract:

Energy efficient and reliable data forwarding becomes important if resources are limited such as in Wireless Sensor Networks. In this paper, we discuss how the error rate associated with a link affects the overall probability of reliable delivery, and consequently the energy associated with the reliable transmission of a single packet. The analysis includes both fixed-power and variable-power scenarios along with the End-to-End Retransmission (EER) and Hop-by-Hop Retransmission (HHR) techniques. In the EER case, a threshold value for the packet error rate at which both scenarios will result in the same energy costs is defined. The relation between this threshold value and the difference in number of hops between both scenarios is also derived. The simulation results finally confirm the theoretical model.

Keywords:

Wireless Sensor Networks, Reliability and Retransmission Techniques

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1. Introduction:

Wireless Sensor Networks are potentially one of the most important technologies of this century. Recent technological advances have led to the emergence of small, low-power devices that integrate sensors and actuators with limited on-board processing and wireless communication capabilities. Pervasive networks of such sensors and actuators open new vistas for constructing complex monitoring and control systems, ranging from habitat monitoring, target tracking, home automation, ubiquitous sensing for smart environments, construction of safety monitoring, and inventory tracking [1].

The key challenge in sensor networks is to maximize the lifetime of sensor nodes that rely on limited battery power. Therefore, computational operations of nodes and communication protocols must be made as energy efficient as possible. Data-centric routing approaches have been proposed in the literature to provide more energy-efficient routing as opposed to the traditional end-to-end routing schemes known as address-centric approaches [1-4]. A comparison between both implementations is given in Table 1.

Table (1): *Data-Centric versus Address-Centric Implementations*

	Data-Centric Implementation	**Address-Centric Implementation**
Communication Mode	Neighbor-to-Neighbor (Hop-by-Hop) Communication	End-to-End Communication
Localized Algorithm?	Yes (no need to maintain overall network topology)[1]	No (rely on global topological knowledge)
Routing Decisions	Based on the contents of the payloads of packets[2]	Based on packets destination addresses

Whereas to compare between two data-centric implementations, points of comparison may include: structure of aggregation tree (planar, cluster, etc), direction of diffusion (push, pull, etc) and type of applications (event-driven, sink-initiated, etc) [1, 5].

Energy-aware routing protocols typically compute the shortest-cost path, where the cost

[1] Local communication implies that, as far as a node knows, the data that is received from a neighbor came from that neighbor. This can be energy efficient in highly dynamic networks when changes in topology need not be propagated across the network.

[2] Nodes store and interpret tasks/data rather than simply forwarding them along.

associated with each link is some function of the transmission (and/or reception) energy associated with the corresponding nodes. To adapt such minimum cost route determination algorithms (such as Dijkstra's or the Bellman–Ford algorithm) for energy-efficient reliable routing, the link cost must now be a function of not just the associated transmission energy, but the link error rates as well [6]. In this research, we analyze the consequences of this behavior with different packet retransmission techniques.

Reliability, as one of the performance measures of routing algorithms for Wireless Sensor Networks, should not be mixed with information accuracy. The later is questioned when data aggregation is used. Data aggregation is the combination of data from different sources according to a certain aggregation function and is an enabler for data-centric routing. It can be categorized into two classes: lossless and lossy [3]. With *lossless aggregation*, all detailed information is preserved. Whereas *lossy aggregation* may discard some detailed information and/or degrade data quality for more energy savings.

The rest of the paper is organized as follows. In section 2, the related work will be described. To understand the effect of introducing link errors to our model, the error-free transmission case is studied first in section 3. In section 4, two generally retransmission techniques are examined. Both sections 3 and 4 represent the analytical model of the work. In section 5, the simulation results for the energy costs of different scenarios will be discussed and compared to the theoretical results. Finally, section 6 will conclude the paper with the possible directions for future work.

2. Related Work:

To route data efficiently in Wireless Sensor Networks, various routing protocols have been proposed. Data-Centric routing is a common routing approach in Wireless Sensor Networks [2, 7, 8, 9]. Factors affecting the performance of data-centric routing, such as the number and placement of sources and the communication network topology, are investigated in [2].

Directed diffusion [7] is a network layer protocol based on data-centric routing. It can be classified as pull-diffusion mechanism. In directed diffusion, the sink broadcasts interests to all sensor nodes in the network. Each sensor node keeps the interest in its local cache and uses the gradient fields within the interest descriptors to recognize the most suitable routes to the sink. These established routes are then used by source nodes to forward the sensed data (events) to the sink.

Robustness is addressed in directed diffusion by enabling *local repair* of failed or degraded paths. Causes for failure or degradation include node energy depletion, and environmental factors affecting communication (*e.g.,* obstacles, rain fade). When the quality of the link between the source and an intermediate node degrades and events are frequently corrupted, the intermediate node negatively reinforces the direct link to the source. This will eventually lead to the discovery of one empirically good path.

Reliable routing has been also tackled in [8] where a new routing scheme, known as EARS; Energy-efficient And Reliable routing Scheme, is proposed. EARS relies on interaction between routing and MAC layers, with the overall goal of achieving energy efficiency and reliability through cross layer optimization.

In EARS, data are forwarded to that neighbor node which has lesser value of the Radio-aware Metric C_{lq}. Each time a Request to Send (RTS) packet is sent to a selected neighbor node. If RTS request is successful, data are routed to that neighbor node, otherwise another neighbor node is selected among the candidate neighbor nodes, which has comparatively less value of the C_{lq}. In this way a route to the corresponding neighbor is selected until the source or the sink is reached.

In this work, modeling of reliable routing in Wireless Sensor Networks is presented. Two scenarios are studied; fixed-power scenario and variable-power scenario. Routing in variable-power scenario, in which each sensor node (source) adjusts its transmission power based on the distance between itself and the receiver (data recipient/sink), has been proposed in a previous work [10]. Simulation results show that more energy savings are achieved in the variable-power scenario than in fixed-power scenario where transmission power is constant and is independent of the characteristics of the link between the transmitter and the receiver.

3. Error-Free Transmission:

In this section, the energy costs of the error-free transmission are presented. The communication model used throughout the analysis can be explained as follows [6]. Let us consider a sender (S) and a receiver (R) separated by a distance D. let N represent the total number of hops between S and R, so that $N - 1$ represents the number of forwarding nodes i: $i = \{2, \ldots, N\}$, with node i referring to the $(i - 1)$th intermediate hop in the forwarding path. Node 1 refers to S and node $N + 1$ refers to R. This is illustrated in Figure 1.

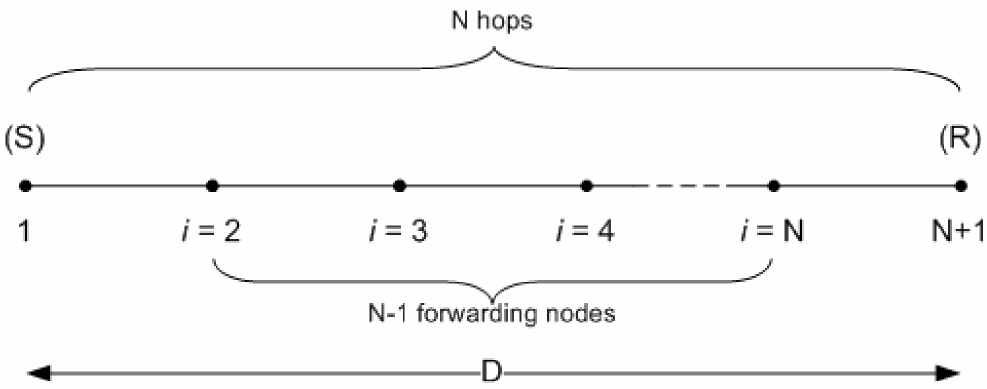

Figure (1): *Communication Model.*

In this case, the total energy spent in simply transmitting a packet once (without considering whether or not the packet was reliably received) from the sender to the receiver over the $N - 1$ forwarding nodes is:

$$E_t = \sum_{i=1}^{N} E_{i,i+1}$$

In the fixed-power scenario, $E_{i,i+1}$ is independent of the link characteristics; in the variable-power scenario, $E_{i,i+1}$ is a function of the distance between nodes i and $i+1$. Thus:

Fixed-Power Scenario

$$E_f = \sum_{i=1}^{N_f} \alpha R^K = \alpha R^K N_f \qquad (1)$$

Variable-Power Scenario

$$E_v = \sum_{i=1}^{N_v} \alpha D_{i,i+1}^K \qquad (2)$$

Where,

R is the communication radius[3]
$D_{i,i+1}$ is the distance between nodes i and $i+1$ ($D_{i,i+1} \le R$)
K is the coefficient of channel attenuation ($K \ge 2$)
α is a proportionality constant

From (1) it is obvious that if links are considered error-free, then minimum hop paths are the most energy-efficient for the fixed-power case. While to understand the tradeoffs associated with the choice of the number of hops in the variable-power case, N_v, it is

[3] All nodes are assumed to be able to communicate with any other nodes that are within some distance called the communication radius.

assumed that each of the hops is of equal length D/N_v. In that case, E_v in (2) is given by:

$$E_v = \sum_{i=1}^{N_v} \frac{\alpha D^K}{{N_v}^K} = \frac{\alpha D^K}{{N_v}^{K-1}} \qquad (3)$$

From (3) it is easy to see that, in the absence of transmission errors, paths with a large number of small hops are typically more energy efficient in the variable-power case. These results are illustrated in Figure 2.

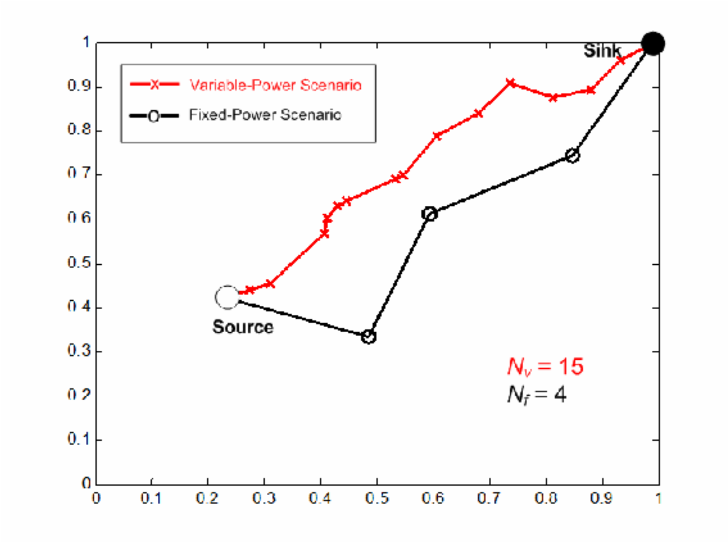

Figure (2): *Fixed-Power Path versus Variable-Power Path.*

It has been confirmed experimentally in [10] that, for a wide range of communication radius and number of sources, E_v is always smaller than E_f while N_v is always larger than N_f.

Definition: Let us define the variable-power gain, G, obtained by using the variable-power scenario as opposed to the fixed-power scenario as follows:

$$G = \frac{E_f}{E_v} = \frac{R^K N_f}{\sum_{i=1}^{N_v} D_{i,i+1}^K} \qquad (4) \quad , \quad \text{and } G \geq 1$$

The value of G depends on the number of sources and the communication radius.

4. Retransmission Techniques:

In the presence of link errors, none of the choices explained in section 3 may give optimal energy efficient paths. In this section, two generally packet retransmission techniques that are used to overcome link errors are examined; namely, the End-to-End Retransmission (EER) and the Hop-by-Hop Retransmission (HHR) techniques [6]. This should not be mixed with the communication modes that are used in combination with data-centric/address-centric implementations given in Table 1.

4.1. End-to-End Retransmission (EER):

In the EER case, a transmission error on any link leads to an end-to-end retransmission over the path. Assuming that each of the *N* links has an independent packet error rate of p_{link}, the probability of a transmission error over the entire path, denoted by *p*, is given by:

$$p = 1 - \text{the probability of an error-free transmission} = 1 - (1 - p_{link})^N$$

The number of transmissions (including retransmissions) necessary to ensure the successful transfer of a packet between *S* and *R* is then a geometrically distributed random variable *X*, such that [6]:

$$\Pr\{X = k\} = p^{k-1} \times (1 - p), \forall k$$

The *mean* number of individual packet transmissions for the successful transfer of a single packet is thus:

$$\text{Mean} = \frac{1}{1 - p}$$

Since each such transmission uses total energy given above by (1) and (2), the total expected energy required in the reliable transmission of a single packet is given by:

Fixed-Power Scenario

$$E_f(EER) = E_f \cdot \frac{1}{1-p} = \alpha R^K N_f \cdot \frac{1}{1-p}$$

Variable-Power Scenario

$$E_v(EER) = E_v \cdot \frac{1}{1-p} = \sum_{i=1}^{N_v} \alpha D_{i,i+1}^K \cdot \frac{1}{1-p}$$

$$\boxed{\therefore E_f(EER) = \frac{\alpha R^K N_f}{(1-p_{link})^{N_f}}} \quad (5)$$

$$\boxed{\therefore E_v(EER) = \frac{\sum_{i=1}^{N_v} \alpha D_{i,i+1}^K}{(1-p_{link})^{N_v}}} \quad (6)$$

Definition: Let us define a threshold value for p_{link} such that:

$$E_f(EER) = E_v(EER) \text{ at } p_{link} = p_{link}(threshold)$$

$$\therefore \frac{\alpha R^K N_f}{(1-p_{link}(threshold))^{N_f}} = \frac{\sum_{i=1}^{N_v} \alpha D_{i,i+1}^K}{(1-p_{link}(threshold))^{N_v}}$$

Using the definition of G in (4) we get:

$$\boxed{p_{link}(threshold) = 1-(G)^{-\frac{1}{\Delta N}}} \quad (7)$$

Where,

$$\Delta N = N_v - N_f \quad , \quad \text{and } \Delta N \geq 0$$

It can be noted that:

For $p_{link} < p_{link}$ *(threshold),* $E_f(EER) > E_v(EER)$

For $p_{link} > p_{link}$ *(threshold),* $E_f(EER) < E_v(EER)$

4.2. Hop-by-Hop Retransmission (HHR):

In the case of the HHR model, the number of transmissions on each link is *independent of the other links* and is geometrically distributed. The total energy cost for the HHR case with N intermediate nodes and having a link packet error rate of p_{link} is:

$$E_t(HHR) = \sum_{i=1}^{N} E_{i,i+1} \cdot \frac{1}{1-p_{i,i+1}}$$

Fixed-Power Scenario

$$E_f(HHR) = \sum_{i=1}^{N_f} \frac{\alpha R^K}{1-p_{link}} = \frac{\alpha R^K N_f}{1-p_{link}} \quad (8)$$

Variable-Power Scenario

$$E_v(HHR) = \sum_{i=1}^{N_v} \frac{\alpha D_{i,i+1}^K}{1-p_{link}} \quad (9)$$

Applying the same assumption in (3), that each hop is of distance D/N_v, to the variable-power equation in (9) we get:

$$E_v(HHR) = \frac{1}{1-p_{link}} \cdot \sum_{i=1}^{N_v} \frac{\alpha D^K}{N_v{}^K} = \frac{\alpha D^K}{N_v{}^{K-1} \cdot (1-p_{link})} \quad (10)$$

From (8), (9) and (10), it can be noticed that the analysis of the hop-by-hop retransmission technique is similar to the analysis of the error-free transmission. Furthermore, similar results are obtained in regards to the relation between the energy costs and the number of hops, i.e. $E_f\,(HHR)$ decreases as N_f decreases whereas $E_v\,(HHR)$ decreases as N_v increases. Obviously, energy costs are higher in HHR case than in error-free transmission providing that $p_{link} > 0$.

5. Simulation Results:

In this section, the simulation results are presented and compared to the theoretical results obtained in sections 3 and 4. For simplifying the analysis, a single-source model is assumed. Routing is thus treated as the *shortest-path problem* in graphs. When two nodes wish to communicate, a *minimum-weight path (shortest path)* connecting the corresponding pair of nodes is selected. The simulation parameters used are shown in Table 2.

Table (2): *Simulation Parameters.*

Number of Nodes	100
Dimensions	square of unit size
Communication radius (*R*)	0.3
Coefficient of channel attenuation (*K*)	2
Proportionality constant (α)	1

The first two parameters represent the same setup used in [2]. The value of the communication radius, *R*, is chosen to be 0.3 to ensure that no experiment may result in unconnected graphs. In our study, we assume free space model with no obstacles, i.e. $K = 2$. Finally, for the purpose of comparison, proportionality constant is assumed to be 1.

5.1. Variable-Power Gain:

The value of the variable-power gain, *G*, defined in (4) is calculated in the error-free transmission case, i.e. p_{link} = 0, by running 100 experiments. Each experiment consists of random placement of 100 nodes including the sink node in a square of unit size. The shortest-path between the source and the sink in fixed-power and variable-power scenarios is obtained using Dijkstra's algorithm. The average of the 100 experiments is then calculated and used to represent the energy costs of each scenario. The value of *G* is computed and found to be:

Variable-Power Gain (*G*) = 3.5

5.2. Energy Costs versus Link Error Rate in EER:

For the end-to-end retransmission case, energy costs of both scenarios are calculated at different values of link error rate, p_{link}, which is varied from 0% to 30% with step of 1%. In this example, ΔN is fixed at a value of 6 (N_v = 9 and N_f = 3). The threshold value of the link error rate, p_{link} *(threshold)*, is obtained experimentally from the intersection of the fixed-power curve with the variable-power curve. Whereas the theoretical value of p_{link} *(threshold)* is obtained by solving equation (7) at ΔN = 6. Both values are shown in Figure 3.

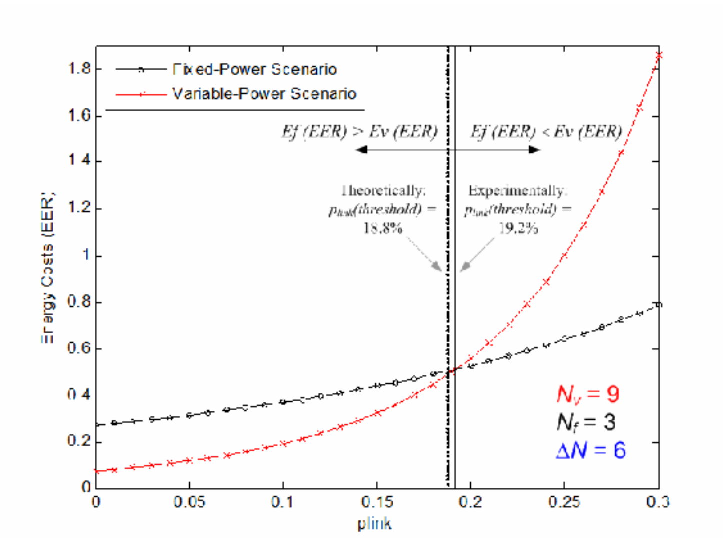

Figure (3): *Energy Costs versus Link Error Rate in EER.*

5.3. Threshold Link Error Rate versus ΔN in EER:

The relation between the threshold value of the link error rate and the difference in number of hops between the variable-power scenario and the fixed-power scenario, Δ*N*, is given by equation (7). To verify this relationship, the same experimental setup discussed above is used. In this case, 300 experiments were run at different values of p_{link}. At each individual value of p_{link}, the value(s) of Δ*N* at which the energy costs of the EER variable-power start to exceed that of the EER fixed-power (or vice versa) was recorded. The results are plotted in Figure 4.

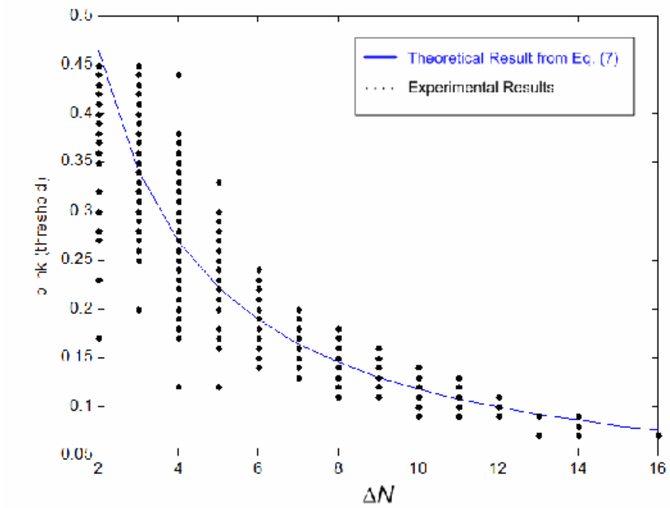

Figure (4): *Threshold Link Error Rate versus ΔN in EER.*

It is worth noting that, using the simulation parameters in Table 2 will result in Δ*N* that varies from 2 to 16. In general, the range of Δ*N* is factor of the density of sensor nodes, the communication radius and the source placement model[4].

5.4. Error-Free Transmission versus EER and HHR:

In this section, the energy costs of the error-free transmission are compared to that of different retransmission techniques. Similar to section 5.2, results are calculated at N_v = 9 and N_f = 3. Figure 5 shows fixed-power scenario represented by equations (1), (5) and (8) for error-free transmission, EER and HHR respectively. Figure 6 shows variable-power scenario represented by equations (2), (6) and (9) for error-free transmission, EER and HHR respectively.

[4] The position of the source(s) in the network.

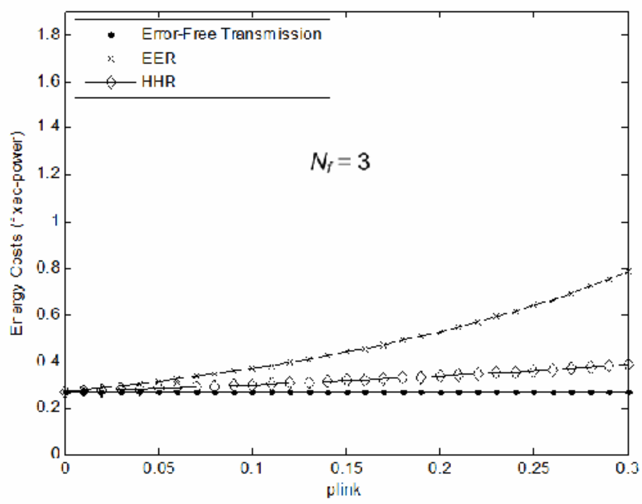

Figure (5): *Error-Free Transmission versus EER and HHR in Fixed-Power Scenario.*

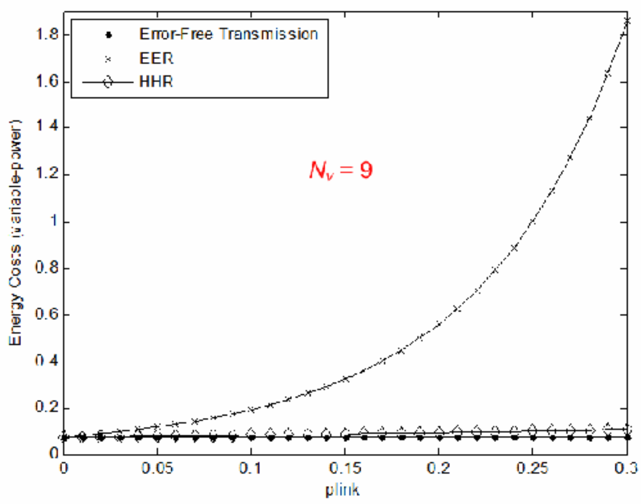

Figure (6): *Error-Free Transmission versus EER and HHR in Variable-Power Scenario.*

It can be noted that in both scenarios the energy costs of HHR case are less than the EER case. This can be explained as follows: in the end-to-end case, the transmission errors on a link do not stop downstream nodes from relaying the packet. Thus, the total energy cost along a path contains a multiplicative term involving the packet error probabilities of the individual constituent links. Whereas in the hop-by-hop case, the number of transmissions on each link is independent of the other links.

6. Conclusion and Future Work:

In this paper, we have modeled and analyzed the performance of reliable routing in Wireless Sensor Networks in both fixed and variable power scenarios. A formula for the threshold value of the link error rate, at which the energy costs of the EER variable-power scenario is equal to that of the EER fixed-power scenario, was derived. A comparison between the simulation results of the error-free transmission, EER and HHR was also presented.

Throughout the simulation, the communication radius was fixed at a constant value. Modeling the effect of the communication radius is a topic for future study. Moreover, the analysis has focused on the case where there is a single source. It is reasonable to ask what would happen if there were additional sources. Extending the analysis to include multiple-sources scenario is part of future research.

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