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RESEARCH ARTICLE - COMPUTER ENGINEERING AND COMPUTER SCIENCE

Computation of the Reliable and Quickest Data Path for Healthcare Services by Using Service-Level Agreements and Energy Constraints

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Abstract

Designing a mission critical system, such as a remote surgery, e-healthcare, e-banking, or e-shopping system, is a challenging task. The continuity and criticality of operation in mission critical systems depend on their delay, capacity, reliability, and energy. In this study, the energy available at each node and the service-level agreements (SLAs) are influenced by the continuity and criticality of data transmission. SLAs are drawn as requested service time and service mean time to failure. For the failure-free operation of mission critical systems, the SLA energy cooperative reliable and quickest path problem (SERQPP) algorithm is defined between a specified source and destination. Analysis indicates that the SERQPP path is a reliable and quickest option for data transmission in remote healthcare applications. The performance of the proposed algorithm is analyzed using mean number of qualifying service set (QSS) paths, average hop count, and average energy efficiency. Simulations are used to determine the variation trends for the SLAs, energy, numbers of nodes, distinct capacities, and data required for the computation of the SERQPP. In the results, it is showing that the number of QSS paths and average energy efficiency are increased with the increase in SLA and energy. In addition to this, quantitative and qualitative comparative study shows that the proposed algorithm outperforms in computation of SERQPP without increasing the time complexity. Finally, the major features of the SERQPP algorithm are discussed and highlighted.

Keywords SLA energy cooperation · Critical healthcare application · Service performance factor · Quickest path problem · Link reliability

1 Introduction

In a progressive society, health-related issues are addressed seriously [1,2]. A high literacy rate is the key drivers in the progress of healthcare sectors. Many e-healthcare services have become strengthened by the R&D activities that have occurred in the area of computer communication networks (CCNs) in the present decade. CCNs are popularly known as the Internet in the literature [3]. Currently, the advancement in Internet technology has catalyzed the implementation of smart and innovative technologies, such as teleportation, telemedicine, and telesurgery. Similar innovations have emerged in areas such as e-banking, e-healthcare, online food delivery, and online shopping [4,5].

In the literature, these applications are sometimes termed as mission critical applications due to the involvement of criticality. The denial of these services ultimately results in considerable loss of life, property, or business [4]. This area of research has drawn the attention of various researchers in the recent past [6] such as homecare [7] and vehicular routing for homecare [8]. The supply of e-healthcare services over the computer communication network (CCN) is an advanced and attractive research topic [6,9–11]. In this scenario, both the service user (patient) and service provider (medical professional or practitioner) are separated by some geographical distance.

In e-healthcare, the satisfaction of the service depends on the quality of communication required between the two specified ends [1,2,12,13]. The content of communication between a patient and medical practitioner is mapped into the data packets within the CCN [14,15]. Here, the quality of healthcare service is considered to be primarily suscepti-

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ble to the connectivity, continuity, and criticality. Therefore, these three attributes have been incorporated in formulating service-level agreements (SLAs) [14,16]. SLAs are a set of rules that define the mutual agreements between a specific service provider (medical practitioner) and service user (patient) [17].

In e-healthcare, the medical practitioner is not physically connected but they are connected to the patient through a dependable communication channel. Thus, the communication channel is responsible for most of the service quality issues. As a result, SLAs have been drawn as requested service time and mean time to failure ($\mathrm{MTTF_s}$) of service for quantifying the service quality issues. The requested service time is the service time up to which a patient can wait for a healthcare service, whereas the $\mathrm{MTTF_s}$ is indicative of the average service time without failure. Both these parameters indicate the level of service performance in terms of the requested service performance factor (RSPF). For simulation purposes, different sets of requested service time and $\mathrm{MTTF_s}$ of service are generated between service providers (medical practitioners) and service users (patients), and the corresponding service criticality between the two ends is evaluated [18].

Continuity is another important aspect for successfully providing healthcare services. According to the concept of continuity, a service must be available for the requested duration. In a service transaction, continuity is treated as a function of the reliability and energy in the corresponding transmission channel [17,19,20]. According to [18], a definite energy level should be maintained for the continuity of data transmission. Communication may fail due to an insufficient amount of energy [21,22], which may lead to severe consequences, such as loss of life, in healthcare services.

1.1 Research Significance

The salient research significance of this paper is as follows:

1. The service assurance is quantified by framing SLAs using the requested service time and $\mathrm{MTTF_s}$ of service. The consideration of SLAs enhances the support for critical services over computer communication network.
2. Energy cooperation is considered as an important parameter for the continuous data transmission for mission critical applications. A sufficient amount of energy is required between the two specified nodes to transmit critical data.
3. The link reliability at the physical level is considered for failure-free critical e-healthcare services. Further, a novel service performance factor is identified by considering all the link performance factors to maximize the reliability of network services such as e-healthcare services
4. The performance of the proposed SLA energy cooperative reliable and quickest path problem (SERQPP) algorithm is evaluated using certain performance parameters, such as the mean number of $s-t$ qualifying service set (QSS) paths, average hop counts, and average energy efficiency.

1.2 Organization

The remainder of the present paper has been structured into six sections—Section 2 explains the background and related work; Sect. 3 is used to explain the proposed system model for SLA energy cooperative reliable and quickest path data transmission problem, and performance analysis is shown in Sect. 4. Simulation results are presented in Sect. 5. Finally, conclusion is presented in Sect. 6.

2 Background, Related Work, and Motivation

The layout of the e-healthcare system is displayed in Fig. 1. The CCN is the core part of the e-healtcare system. Generally, a CCN is modeled using a network topology having a set of nodes and links. Each node is represented by a computer, router, switch, or user. Each link represents a connection between two consecutive nodes. In any CCN application, data are transmitted between two ends [23].

As displayed in Fig. 1, a medical practitioner (source) is connected with the patient (destination) through a communication network, where data related to the health condition may flow in any direction. Initially, the communication network was restricted to a few network services due to resource constraints and lack of innovation [24]. During the initial phases, e-healthcare services were difficult to implement because the network was slow and connection was limited. Gradually, such services became possible with the evolution of protocols based on quickest path algorithms. Various researchers have contributed to the evolution of quality-oriented services over the CCN [23–31].

The QPP was developed by considering the bi-criterion concept for a large number of data transmission services [25]. Most of the aforementioned literature highlights only single-pair QPP data transmission services. Many new applications have been achieved by extending a single-pair QPP into an all-pair or many-pair QPP [26]. Efforts have also been made to accommodate additional constraints in data transmission services without increasing the time complexity [27]. Many extended forms of the QPP algorithm, such as k-QPP, are available [28,29]. Numerous scenarios were surveyed by [30] to obtain a deep insight into the QPP algorithm. An important application of the QPP algorithm is the building evacuation problem during emergency situations [31]. However, due to

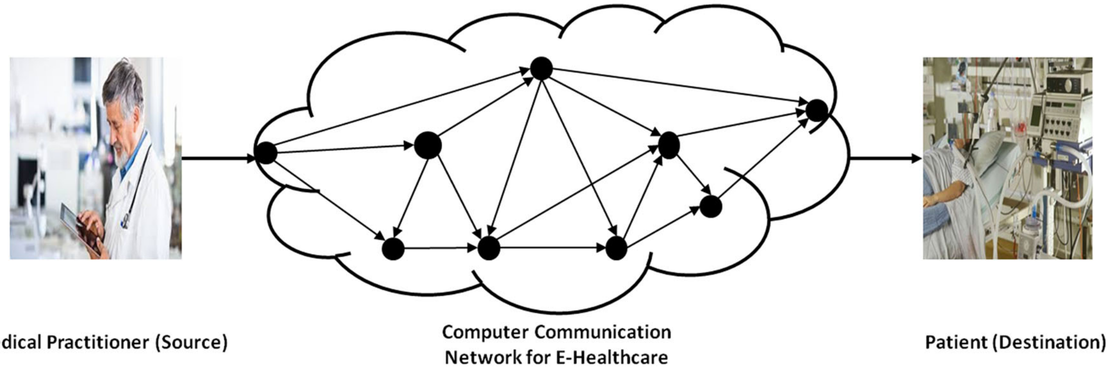

Fig. 1 e-healthcare system

some uncertainties, the application of computer networks is not preferred for mission critical purposes.

By considering additional performance parameters, the quickest data transmission protocols based on the QPP could support teleoperation and telepresence services [32]. Therefore, a network planner or designer should consider the time sensitivity together with the reliability or failure-free operation to successfully provide these services [28,40–44]. The consideration of reliability in network data transmission was pioneered in [33] and appeared as a cost–reliability ratio problem. Later, for the first time, the QPP algorithm was proposed with reliability for data transmission services [34]. Two polynomial algorithms, namely the most reliable QPP and quickest most reliable path problem, were proposed in [34]. Similarly, a formulation was presented by [35] as a most reliable data transmission path. Moreover, some related studies have evaluated the reliability of flow networks [36]. Numerous other algorithms are available in the literature to solve this problem [27,37–39], and research is ongoing for developing new applications.

Network connectivity depends on various performance parameters, such as the reliability, capacity, and delay. The energy or power required for the transmission must be satisfied. Energy may not be always be available. If energy is unavailable, transmission deteriorates, which may lead to a catastrophic situation, particularly in the case of e-healthcare services. Therefore, the energy or power required for the e-healthcare system should be considered. To the best of our knowledge, energy was considered in data path transmission for the first time in [19]. This approach was further extended in [21] as a node–energy–maximization problem. The energy, reliability, availability, and risk were considered for data transmission in [40,41]. In communication, energy constraints have been proposed in the form of green energy, especially due to the efforts of the environmentalists [10]. Recently, [17] considered the energy when computing the QPP for finding risk violation factors corresponding to different data traffic values. This problem has been studied as a quality of service path problem [10,16,56,57]. Routing protocols developed on the basis of the reliability and QPP can support the real-time applications over transportation networks, power grid networks [42], CCNs [39], manufacturing networks [43,44], and wireless ad hoc networks [45]. With the aforementioned developments, mission critical services, such as e-healthcare services, can be provided [2].

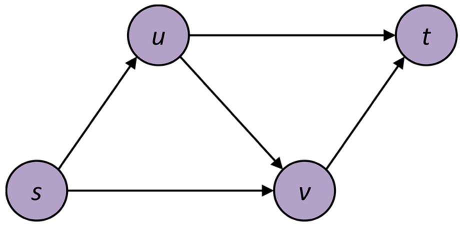

Fig. 2 A computer communication network representation as a Graph

The preliminary details discussed in the following paragraphs are important for laying the foundation for the development of the network-based e-healthcare services model.

Consider a CCN modeled with the help of a graph $G = (N, E)$, as displayed in Fig. 2, where N is the set of nodes and E is the set of the links. Two specific nodes are designated as source (s) and terminal (t) nodes to transmit σ units of data. Each link (u, v) between any two adjacent nodes u and v is assigned with a single weight [either reliability $r_l(u, v)$, capacity $c(u, v)$, or delay $d(u, v)$]. Moreover, a link can be assigned multiple weights [as a combination of reliability $r_l(u, v)$, capacity $c(u, v)$, and delay $d(u, v)$]. The reliability of the link [$r_l(u, v)$] is the probability of failure-free transmission, capacity of the link [$c(u, v)$] is the rate of data transmission, and delay time [$d(u, v)$] is the lag time corresponding to the data transferred over the link (u, v). Let us assume that σ units of data are transmitted along the link (u, v) at a constant flow rate [$\rho \leq c(u, v)$] between two consecutive nodes u and v of a link (u, v). $T_\sigma(u, v)$ represents the minimum transmission time along a link (u, v). $T_\sigma(u, v)$ has the maximum flow rate and can be given as follows [46]:

$$T_\sigma(u, v) = d(u, v) + \left\lceil \frac{\sigma}{c(u, v)} \right\rceil \tag{1}$$

Let the $s - t$ path (P) be defined as series sequence of links [i.e., $(s = u_1, u_2, u_3 \ldots\ldots, u_k = t)$], where $u_i \in N, i = 1, \ldots\ldots, k$ and $(u_i, u_{i+1}) \in E,\ i = 1, \ldots, k-1$ form a loop-less path from source "s" to destination "t". Minimum transmission time along P for transmitting the data with a constant flow rate (without any buffering) is given as [46]:

$$T_\sigma(P) = d(P) + \frac{\sigma}{c(P)} \tag{2}$$

In Eq. (2), $d(P)$ and $c(P)$ are related to the path values, where

$$d(P) = \sum_{i=1}^{i=k-1} d(u_i, u_{i+1})$$

and

$$c(P) = \min\nolimits_{i=1,\ldots,k-1} c(u_i, u_{i+1}).$$

Equation (2) can be further extended as follows [46,47]:

$$T_\sigma(P) = \sum_{i=1}^{k-1} d(u_i, u_{i+1}) + \left\lceil \frac{\sigma}{\min\limits_{i=1,2,\ldots,k-1} c(u_i, u_{i+1})} \right\rceil \tag{3}$$

Using the aforementioned equations, the QPP can be formulated for the transmission services [24,46] as follows:

$$\begin{gathered} \min_{p} T_\sigma(P) \\ \text{s.t. } P \text{ is an } s - t \text{ path in the network } G \end{gathered} \tag{4}$$

For designing a failure-free QPP to support healthcare data transmission services, the link reliability $[r_l(u, v)]$ plays an important role in determining the failure-free quickest data transmission service path for e-healthcare. Therefore, the proposed QPP should be transformed as a reliable QPP (RQPP) having the reliability of path P [34].

$$R_l(P) = \prod_{i=1}^{k-1} r_l(u_i, u_{i+1}) \tag{5}$$

In the beginning, CCNs were meant only for general-purpose applications, such as transfer of data according to the store and forward mechanism. Hence, attention was not given to the continuity and criticality of applications and services. Due to advancement in the field of networking, CCNs can now remotely support the execution of various mission critical services.

Due to the integration of various criticalities involved in e-healthcare applications, service assurance is necessary. Attempts have been made to define service assurance [20,48]. In [20,48], service assurance is defined in terms of SLAs. Similarly, the authors in [17] considered SLAs for computing the QPP as requested service time and $\mathrm{MTTF_s}$ of a service. The approach used by [17] is defined as SLA and energy cooperation. Various other approaches have been proposed for formulating and computing SLAs [15,49,50].

In this study, we aim to compute the reliable and quickest path for the promising e-healthcare services.

3 Proposed System Model

In most cases, a sufficient amount of energy is always assumed to be available in a general-purpose CCN for the data transmission. However, in practical scenarios, the energy is limited during any type of data transmission over the CCN [19]. Hence, this scenario may lead to degradation in the transmission performance. Recently, authors have proposed energy-based modeling approaches for data transmission [19].

In this study, we consider the energy in the e-healthcare system as well as other design parameters. When data related to e-healthcare are transmitted, various uncertainties in the form of natural and manmade disasters may degrade the service performance. Therefore, designing a dependable network is highly recommended. In this study, the concept of SLAs is used to ensure performance according to the service request. In the following system model, energy and SLAs cooperation are proposed for e-healthcare services.

The following assumptions are made for developing the system model for e-healthcare data transmission:

1. Data transmission is along the series sequence of links (i.e., without the consideration of parallel links or self-loops).
2. Nodes are perfect with respect to the breakdown failure. However, the nodes are not considered perfect with respect to the performance-related failure.
3. Link capacities are s-independent.
4. Conservation law is obeyed for the flows in the network.

3.1 SLA Mapping and Service Performance Factor

In the competitive era, SLA cooperation plays a significant role in the e-healthcare. The completion of service is considered in different terms [48]. SLAs are mapped into the requested service time (t_s) and service $(\mathrm{MTTF_s})$ during problem formulation. SLAs may be defined for any duration (i.e., in terms of seconds, hours, months, or years). In CCNs, data transmission services may occur for a fraction of seconds. Therefore, the unit for the considered SLAs is taken as seconds.

The data transmission performance of an e-healthcare system depends on the delay and capacity associated with a link. To enhance the performance, all the link performance components are combined as the service performance factor (SPF) of the link [5]. The SPF is considered equivalent to the link reliability that can represent both breakdown and performance failures. Therefore, SLAs are modeled in terms of the link reliability [51]. The residual service performance factor (RSPF) at the nodes (r_u) is defined as the probability of failure-free service performance for a requested service time (t_s). The RSPF at the nodes is represented by the following equation:

$$r_u = \mathrm{e}^{-\frac{t_s}{\mathrm{MTTF}_s}} \tag{6}$$

During the data transmission service, performance failure occurs when the delay in data transmission crosses the limit of the requested service time ($\mathrm{MTTF_s}$). Performance failure can be expressed by using two basic factors, namely the (i) total transmission time and (ii) MTTF of a link [5,52]. Therefore, the mapping of the SPF of the link is represented as follows:

$$r_s(u, v) = \mathrm{e}^{-\left[\frac{d(u,v)+\frac{\sigma}{c(u,v)}}{\mathrm{MTTF(u,v)}}\right]} \tag{7}$$

The analysis of the SPF [$r_s(u, v)$] is discussed with the help of two main cases in the following text.

Ideal Case 1 Let us consider that the minimum transmission time along a link is very small [i.e., equal to 0; $T_\sigma(u, v) \cong o$]. According to this assumption, the calculated SPF is 1. Hence, the SPF has a maximum value.

Ideal Case 2 Let us consider that the minimum transmission time along a link is very high [i.e., close to infinity; $T_\sigma(u, v) \cong \infty$]. As per this assumption, the calculated SPF is equal to 0. Hence, the SPF has a minimum value.

The aforementioned cases indicate that the SPF is comparable to the link reliabilities, which lie in the worst and best cases, that is, $r_s(u, v) \in [0, 1]$.

The SPF of path P is computed by substituting Eq. (2) into Eq. (7).

$$R_s(P) = \mathrm{e}^{-\left[\frac{T_\sigma(P)}{\mathrm{MTTF(P)}}\right]} \tag{8}$$

If the delay is not considered, the proposed system model provides the most reliable SLA and energy cooperative data transmission path.

3.2 SLA Cooperation

A network node may represent a user, service provider, router, or switch. In the given scenario, data transmission occurs along a series sequence of links of path P, and SLAs should be satisfied between two consecutive links. To satisfy SLAs in e-healthcare services, each node of the CCN is endowed with the RSPF (r_u). The SLA constraint follows the equality along a link (u, v).

$$\mathrm{e}^{\frac{-\left[d(u,v)+\frac{\sigma}{c(u,v)}\right]}{\mathrm{MTTF(u,v)}}} \geq r_u, \quad \forall (u, v) \in E \tag{9}$$

The residual RSPF (RRSPF) along a link is given as follows:

$$\mathrm{e}^{\frac{-\left[d(u,v)+\frac{\sigma}{c(u,v)}\right]}{\mathrm{MTTF(u,v)}}} - r_u \geq 0, \quad \forall (u, v) \in E$$

The RRSPF can be used to identify the SLA cooperative links for data transmission.

Similarly, the RRSPF [$r_u(\sigma, P)$] value for a path (P) can also be defined as the residual value of the SPF with respect to the RSPF.

In this study, we apply SLA cooperation and the framework of the extensive reliability theory to enhance the service performance. The RRSPF [$r_u(\sigma, P)$] along a path (P) indicates the feasibility [i.e., $r_u(\sigma, P) \geq 0,\ \forall\, u \in P$] of the path as follows:

$$r_u(\sigma, P) = \begin{cases} -\ln(r_u) - \left\{ -\ln\left[\mathrm{e}^{\frac{-\left[d(u_i,u_{i+1})+\frac{\sigma}{c(P)}\right]}{\mathrm{MTTF}(u_i,u_{i+1})}} \right] \right\}, & \text{if } u = u_i,\ i = 1, 2, .,\ k-1 \\ -\ln(r_u) & \text{otherwise} \end{cases} \tag{10}$$

3.3 Energy Cooperation

In a CCN, the requested energy at node u is known as the energy rate [$\omega(u, v)$] for transmitting σ units of data over a link (u, v). The requested energy is calculated as $\omega(u, v)\frac{\sigma}{c(u,v)}$. Each node ($u \in N$) is associated with a limited energy supply (P_u) [21]. To satisfy the energy constraint, the associated energy supply should be more than or equal to the requested energy.

$$P_u \geq \omega(u, v)\frac{\sigma}{c(u, v)}, \quad \forall (u, v) \in E \tag{11}$$

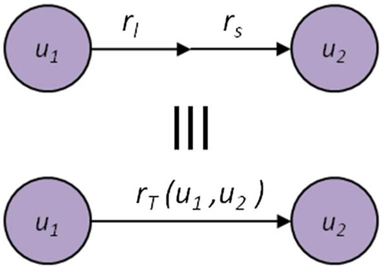

Fig. 3 Framework of reliability using the link reliability and SPF

The remaining value is termed as the residual energy supply (RES) along a path $P_u(\sigma, P)$. The RES is defined as the remaining endowed energy supply from the requested energy with nodes after complete data transmission along a path. The role of the RES is to find the energy cooperative nodes that participate in data transmission [19]. The RES $[P_u(\sigma, P)]$ along path P indicates the feasibility of path P [i.e., $P_u(\sigma, P) \geq 0, \forall u \in P$] as follows:

$$P_u(\sigma, P) = \begin{cases} P_u - \omega(u_i, u_{i+1})\frac{\sigma}{c(P)}, & \text{if } u = u_i, i = 1, \ldots, k-1 \\ P_u & \text{otherwise} \end{cases} \tag{12}$$

Remark The capacity of the path is considered different from the link capacity because calculations are performed over the subnetworks, which are sorted with distinct capacities. Therefore, for any subnetwork, the links capacity $[c(u, v)]$ is the same as the path capacity $[c(P)]$, and the path capacity is the minimum capacity of any link (u, v) along a path in the subnetwork.

In this study, the total link reliability $[r_T(u, v)]$ for transmitting œ units of data depends on link reliability $[r_l(u, v)]$, i.e., probability of hard failure, and SPF $[r_s(u, v)]$, i.e., probability of soft failure. As both reliabilities are modeled into series events, the total link reliability is calculated as follows:

$$r_T(u, v) = r_l(u, v) \times r_s(u, v) \tag{13}$$

The graphical representation of Eq. (13) is illustrated in Fig. 3.

The total path reliability is obtained by substituting the values from Eqs. (5) and (8) into Eq. (14). The graphical presentation of Eq. (14) is illustrated in Fig. 4.

$$R_T(P) = \prod_{i=1}^{k-1} \left\{ r_l(u_i, u_{i+1}) \times e^{-\left[\frac{T_\sigma(u_i, u_{i+1})}{\mathrm{MTTF(u_i, u_{i+1})}}\right]} \right\} \tag{14}$$

The aforementioned expression of the total path reliability is the novel cost function that provides the SERQPP with the maximum performance.

$$\begin{aligned} &\min_{\mathrm{P}} \{-\ln [R_T(P)]\} \\ &\text{s.t. } r_u(\sigma, P) \geq 0, \;\; u \in P \\ &P_u(\sigma, P) \geq 0, \;\; u \in P \\ &P \text{ is an } s - t \text{ path in network } G \end{aligned} \tag{15}$$

In this study, the minimization problem is formulated because it uses the property of Dijkstra's algorithm to compute the $s - t$ paths. Therefore, to map the performance (from maximum to minimum), the negative logarithm (−ln) to the cost function is used.

4 Performance Analysis and Algorithm

Generally, there exist r different capacities ($c_1 < c_2 < \cdots < c_r$) in any CCN. The minimum SLA and energy-satisfied capacity of link capacity are represented by Eqs. (16) and (17), respectively. The minimum SLA energy-satisfied capacity of links is expressed in Eq. (18).

$$c_{\mathrm{minSLA}}(u, v) = \min_{i=1,\ldots,r} \left\{ c_i \; : \; \mathrm{e}^{\frac{-\left[d(u,v) + \frac{\sigma}{c_i}\right]}{\mathrm{MTTF(u,v)}}} - r_u \geq 0 \right\} \tag{16}$$

By using Eq. (16), the SLA cooperation procedure for sorting the links to support the critical applications is represented as follows:

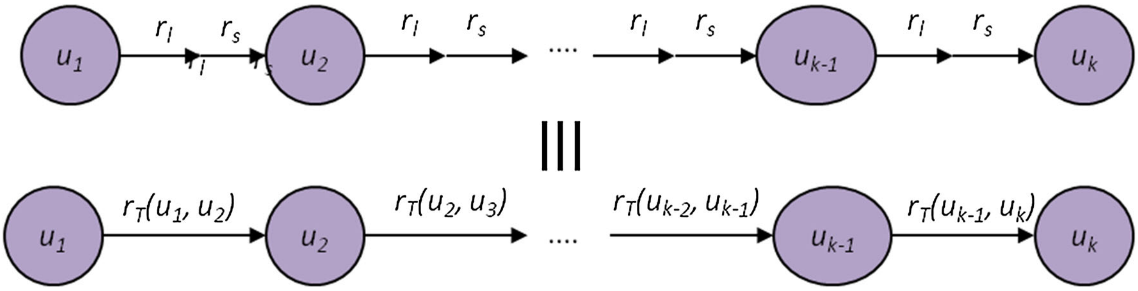

Fig. 4 Model to compute the total reliability of the path

Procedure: Minimum SLA satisfied capacity

```
Input: $G(N, E), c, d, MTTF, s-t, t_s, MTTF_s$.
Output: Minimum SLA satisfied capacity
Begin {
1.  Compute RSPF at nodes $r_u$.
2.  Compute SPF at links having distinct capacities.
3.  Find minimum SLA satisfied link capacity, i.e.,
      $c_{minSLA}(u, v)$ after satisfying equation (16).
} End
```

$$c_{\mathrm{minE}}(u, v) = \min_{i=1,\ldots,r} \left\{ c_i \ : \ P_u - \omega(u, v)\frac{\sigma}{c_i} \geq 0 \right\} \tag{17}$$

Equation (17) helps to incorporate efficient energy use in continuous data transmission. The procedure for the support of continuity is given as follows:

Procedure: Minimum energy-satisfied capacity

```
Input: $G(N, E), c, d, \omega, s-t, P_u$.
Output: Minimum energy-satisfied capacity
Begin {
1.  Compute energy at nodes $P_u$.
2.  Compute energy at links having distinct capacity.
3.  Find minimum energy-satisfied link capacity, i.e.,
      $c_{minE}(u, v)$ after satisfying equation (17).
} End
```

$$\begin{aligned} c_{\min}(u, v) = \min \big\{ &\left[c_{\mathrm{minE}}(u, v) \geq c_a \geq c(u, v)\right] \\ &\cap \left[c_{\mathrm{minSLA}}(u, v) \geq c_b \geq c(u, v)\right] \big\} \end{aligned} \tag{18}$$

where c_a and c_b are the capacities that lie in the minimum cooperative energy and SLA capacities, and link capacity, respectively. Equation (18) indicates the minimum link capacity required to support continuity and criticality in data transmission if $c_{\mathrm{minSLA}}(u, v)$ and $c_{\mathrm{minE}}(u, v) > 0$. An $s-t$ path (P) is feasible if $c(P) \geq c_{\min}(u, v)$.

The aforementioned equations sort the minimum capacity that incorporates both critical and continuous data transmission by considering the AND rule. The AND rule is considered because for a specific link, both SLA and energy parameters must be satisfied. When a link supports any parameter, the logic is given a value of 1; otherwise, the logic is given a value of 0. According to the property of the AND gate, the link supports the minimum capacity $c_{\min}(u, v)$ only when both parameters have logic "1". Therefore, $c_{\min}(u, v)$ has to follow the AND rule for the SLA energy cooperative reliable and quickest data transmission problem in mission critical applications.

The procedure for incorporating both the aforementioned parameters for sorting the minimum link capacity is given as follows:

Procedure: Minimum SLA Energy-Satisfied capacity using AND rule

```
Input: $G(N, E), c, d, \omega, MTTF, s-t, t_s, MTTF_s, P_u$.
Output: Minimum SLA Energy-Satisfied capacity using AND rule
Begin {
1.  Find RSPF $r_u$ and energy $P_u$ at nodes.
2.  Compute SPF and energy at links having distinct capacities.
3.  Compute minimum capacity using intersection between
      minimum SLA and minimum energy-satisfied capacities
      of links, i.e., $c_{min}(u, v)$ using equation (18).
} End
```

According to Eq. (18), r number of subnetworks are sorted, and each link must follow the given inequality for the path capacity $c(P)$.

$$c(u, v) \geq c_j \geq c_{\min}(u, v); \quad \text{where } j = 1, 2, \ldots, r \tag{19}$$

Lemma 1 *Let a path $P = u_1, u_2 \ldots, u_{k-1}, u_k$ has been known as the $s-t$ path in a subnetwork, and then, that path has been called as SLA energy cooperative SERQPP.*

Proof Path P is $s-t$ path in the subnetwork; the capacity of path $c(P)$ has to follow $c(P) \geq c_j \geq c_{\min}(u_i, u_{i+1})$, where $i = 1, \ldots, k-1$. Hence,

$$\begin{aligned} P_u(\sigma, P) &= P_u - \omega(u_i, u_{i+1})\frac{\sigma}{c(P)} \\ &\geq P_u - \omega(u_i, u_{i+1})\frac{\sigma}{c_{\min}(u_i, u_{i+1})} \geq 0 \\ r_u(\sigma, P) &= \mathrm{e}^{\frac{-\left[d(u_i, u_{i+1}) + \frac{\sigma}{c(P)}\right]}{\mathrm{MTTF}(u_i, u_{i+1})}} - r_u \\ &\geq \mathrm{e}^{\frac{-\left[d(u_i, u_{i+1}) + \frac{\sigma}{c_{\min}(u_i, u_{i+1})}\right]}{\mathrm{MTTF}(u_i, u_{i+1})}} - r_u \geq 0 \end{aligned}$$

For the nodes which have not been accounted in the path, the endowed parameters remain same. Therefore, for a path surplus service performance factor and residual energy follows this. □

Lemma 2 *Let a $s-t$ path P is said to be a feasible path with path capacity $c(P) = c_j$, and then, P is said to be a path in G_j.*

Proof Using Lemma 1, let P is feasible.

$$\begin{aligned}P_u(\sigma, P) &= P_u - \omega(u_i, u_{i+1})\frac{\sigma}{c(P)}\\ &\geq 0, i = 1, 2, \ldots, k-1\\ r_u(\sigma, P) &= \mathrm{e}^{\frac{-\left[d(u_i,u_{i+1})+\frac{\sigma}{c(P)}\right]}{\mathrm{MTTF}(u_i,u_{i+1})}} - r_u\\ &\geq 0,\ i = 1, 2, \ldots, k-1\end{aligned}$$

Hence, $c_{\min}(u_i, u_{i+1}) \leq c(P) = c_j \leq c(u_i, u_{i+1})$, where $i = 1, \ldots, k-1$, and (u_i, u_{i+1}) are in the path with sorted links of G_j; hence, P is an $s-t$ path. ◻

In this study, for any given network topology, the major concern of the routing is to find the SERQPP path (P). The reliability of the path depends on the computation of the shortest path problem (SPP). The solution of the SPP is obtained with Dijkstra's algorithm by using the link cost function of the SPF $[r_s(u, v)]$ in the subnetwork graph G_j. However, the algorithm considers the minimum cost values. Therefore, $-\ln$ is used to minimize the problem.

$$\begin{aligned}&\mathrm{SPP_j}\ :\ \min_P \{-\ln[R_s(P)]\}\\ &\text{s.t. } P \text{ is an } s-t \text{ path in the network } G_j\end{aligned} \tag{20}$$

Lemma 3 *Let P be an optimal path solution of* $\mathrm{SPP_j}$ *and $c(P) = c_h > c_j$. Then, there is no other optimal solution for the SERQPP with capacity c_j.*

Proof Let Q be a $s-t$ feasible path for the SERQPP path with capacity c_j then Q is a path in G_j.

$$\begin{aligned}R_T(P) &= R_l(P).e^{\frac{-\left[d(P)+\frac{\sigma}{c_h}\right]}{\mathrm{MTTF}(P)}}\\ &< R_l(Q).e^{\frac{-\left[d(Q)+\frac{\sigma}{c_j}\right]}{\mathrm{MTTF}(P)}} = R_T(Q)\end{aligned}$$

Therefore, Q cannot be an optimal solution for the SERQPP.

Theorem 1 *Let $\check{P}$ be an optimal solution of the SERQPP and $(\check{P}) = c_h$. Then, $\check{P}$ is an optimal solution of* $\mathrm{SPP_h}$, *and any optimal solution of* $\mathrm{SPP_h}$ *is an optimal solution.*

Proof Because $\check{P}$ is an $s-t$ feasible path for the SERQPP having a capacity c_h, $\check{P}$ is an $s-t$ path in G_h. Let Q be an $s-t$ feasible path in the network G_h, and then, $c(Q) \geq c_h$. If $d(Q) < d(\check{P})$, then

$$\begin{aligned}R_T(Q) &= R_l(Q).\mathrm{e}^{\frac{-\left[d(Q)+\frac{\sigma}{c(Q)}\right]}{\mathrm{MTTF}(Q)}}\\ &< R_l(\check{P}).\mathrm{e}^{\frac{-\left[d(\check{P})+\frac{\sigma}{c_h}\right]}{\mathrm{MTTF}(\check{P})}} = R_T(\check{P}),\end{aligned}$$

which disprove the optimality of $\check{P}$. Furthermore, by applying Lemma 3, the capacity of any $s-t$ shortest path $(\tilde{P})$ in G_h is $c(\tilde{P}) = c_h$. Hence, $\tilde{P}$ is an $s-t$ feasible path for SERQPP such that $R_T(\tilde{P}) = R_T(\check{P})$ is an optimal solution. ◻

4.1 Flowchart of the SERQPP

The flowchart of the proposed algorithm is illustrated in Fig. 5. This flowchart is supportive in designing aspect of an algorithm for the SERQPP.

4.2 Algorithm

```
Algorithm 1: SERQPP Algorithm
Input: $G(N,E), \sigma, r_l(u,v), c(u,v), d(u,v), MTTF(u,v), \omega(u,v), r_u, P_u, t_s$ and $MTTF_s$
Output: SERQPP data transmission or null.
BEGIN{
Initialization:
$j \leftarrow 1$,
Procedure:
STEP0: Variable Declaration
$G \leftarrow$ Directed Network
$N \leftarrow$ Set of nodes
$E \leftarrow$ Set of links
$r_l(u,v) \leftarrow$ Reliability of the link $(u,v)$
$c(u,v) \leftarrow$ Capacity of the link $(u,v)$
$d(u,v) \leftarrow$ Delay of link the $(u,v)$
$\omega(u,v) \leftarrow$ Energy rate of link the $(u,v)$
$P_u \leftarrow$ Endowed power at nodes $u$
$r_u \leftarrow$ Requested service performance factor at nodes $u$
$t_s \leftarrow$ Requested service time
$MTTF_s \leftarrow$ Mean Time to Failure of service
$MTTF(u,v) \leftarrow$ Mean Time to Failure of a link
STEP1: Prune $r$ different capacities of links corresponds to critical-continuous service & label of minimum capacity:
(i)     $c_1 < c_2 < c_3 \cdots < c_r$
(ii)    $c_{min}(u,v)$ with AND rule
STEP2: Solve $SPP_j$ w.r.t. SPF $r_s(u,v)$ in $G_j$ with capacities $c_j$
for $j \leftarrow 1{:}r$
        Set $j \leftarrow 1$
        Solve $SPP_j$
            if No $s-t$ path in $G_j$ with capacity with $c_j$
                go to STEP3
            else
                Let $P_j$ is an optimal solution for SPP$_j$ with capacity $c(P_j) = c_j$
            end
end
STEP3:
if $j = r$
        go to STEP4
else
        set $j = j + 1$ and go to STEP2
end
STEP4: Find the solution
Find index $h \in (1, 2, \ldots r)$ of path array $P_j$ such that
        $-\ln[R_T(P_h)] = \min_{j=1,\ldots,r} -\ln[R_T(P_j)]$
$P_h$ is an optimal solution of the SERQPP
} END
```

Theorem 2 *The proposed SERQPP algorithm is having the time complexity of $O(r(m + n(\log(n)))$.*

Proof The SERQPP is elaborated with the help of various steps which are involved in explanation of working. In very first step, STEP 0 is used to declare the variables. The sorting of subnetwork graphs is carried out in STEP 1 after fulfilling the constraints. Different subnetwork graphs are sorted according to the distinct capacities in the network. In STEP 2, the SPF of the sorted arcs is pruned from different subnetwork graphs. Dijkstra's algorithm (SPP_j), which has a time complexity of $O(m + n(logn))$ [53], is run in STEP 3 and STEP 4. Dijkstra's algorithm is run for the r different subnetwork graphs; therefore, the proposed algorithm is having

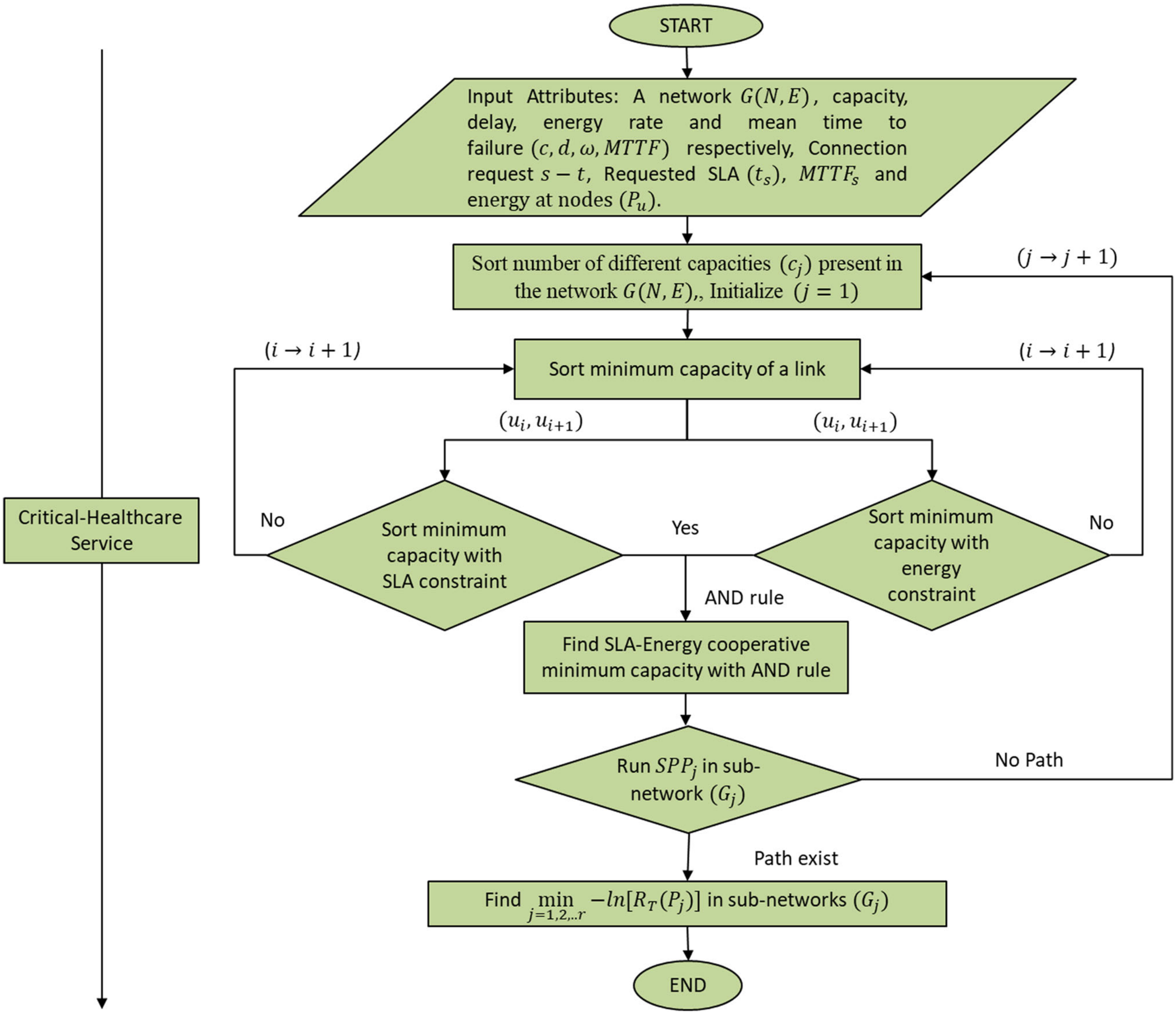

Fig. 5 Flowchart for the proposed SERQPP algorithm

the complexity of $O(r(m+n(log(n))))$. Finally, in STEP 5, comments are made on the minimum logarithmic total path reliability. □

5 Simulation Results

5.1 Experiment Setup

The experiment is conducted in MATLAB 2010a on a personal computer comprising an Intel(R) Core^{TM} i5-7400 CPU with a 3.00-GHz processor, 8-GB RAM, and the operating system Windows 10. The SERQPP algorithm involves the computation of path by using Dijkstra's algorithm. The scope of the proposed model is simulated using the hop count, QSS paths, and energy efficiency. For understanding the applicability and usefulness of the proposed algorithm, the results for the standard topology and random networks generated by the Waxman random topology generator are presented.

5.1.1 Standard Topology

An SLA energy-satisfying service is simulated on the standard directed network topology of the 24-node USANET with source $(s) = 1$ and destination $(t) = 24$, as displayed in Fig. 6 [54].

Each link of the topology is associated with the delay, capacity, reliability, MTTF, and energy rate. The link delay and capacity are considered to have a uniform distribution range of [1,100] in s and Mb/s, respectively. The values of the link reliabilities are taken from the uniform distribution range of [0, 1]. The MTTF values associated with the

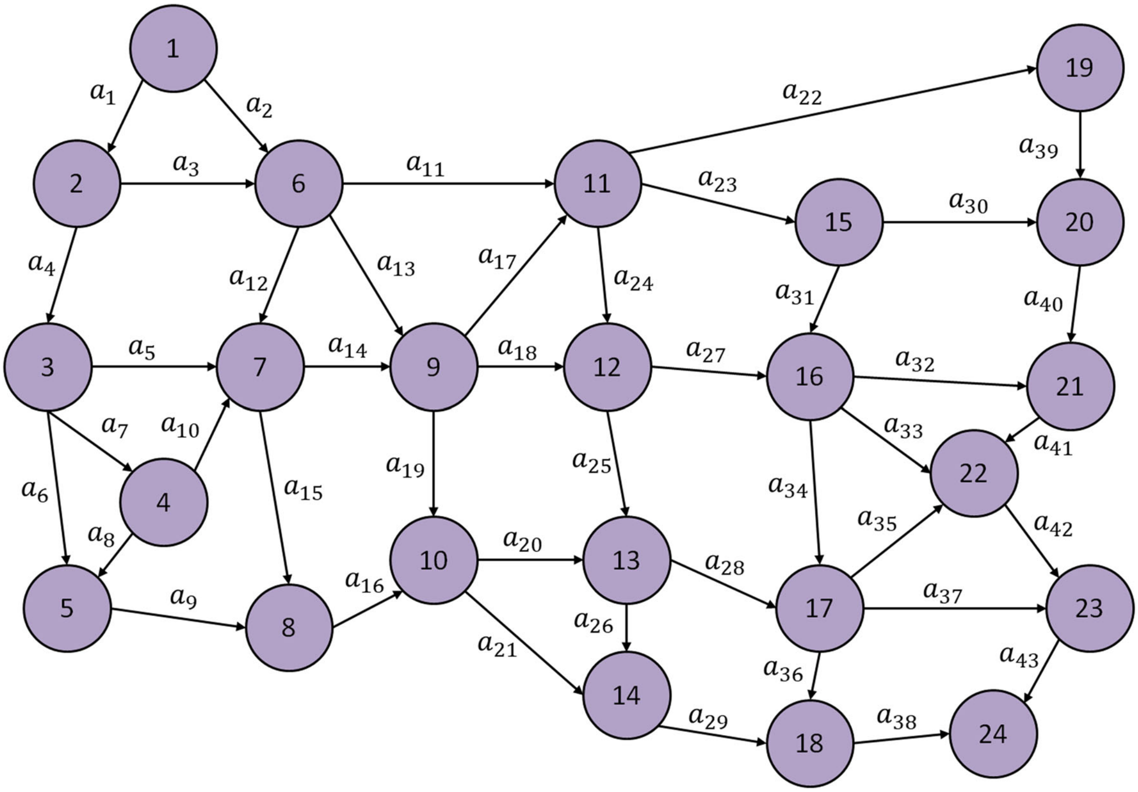

Fig. 6 Network topology of the 24-node USANET directed network with $s = 1$ and $t = 24$

links are considered to have a uniform distribution range of [1,100] s. When transmitting 100 Mb of data between different links and nodes, let each node be associated with a fixed energy (i.e., P_u) of 3×10^7 J and fixed RSPF (r_u). The energy rate $[\omega(u, v)]$ at each link is calculated from the relation $10^{-4}c(u, v)d^2(u, v)$. The requested SLA for the data transmission is requested service time $(t_s) = 100$ s and service $\mathrm{MTTF_s} = 500$ s.

5.1.2 Waxman Random Topology Generator

To analyze the performance of the proposed SERQPP algorithm on large random networks, a Waxman random topology generator is used [55,56]. The Waxman topology is generated by placing the nodes in a one-by-one square, and links are created between two nodes u and v by considering the probability.

$$P(u, v) = \alpha \mathrm{e}^{-(\frac{d(u,v)}{\beta L})} \tag{21}$$

where $d(u, v)$ is the Euclidean distance between (u) and (v),

α is the maximal link probability such that $\alpha > 0$,
β is a parameter that controls the length of the links, and
L is the maximum distance between any two stations.
The values of α and β are considered as 0.4 and 0.1, respectively.

The different link parameters are considered to have the same value as in the aforementioned example. To enhance the clarity of results, different values of data traffic, energy, and SLAs are considered. The proposed algorithm is verified for different network dimensions, such as the number of nodes, number of links, distinct capacities, energy at nodes, data traffic, and SLAs. The values for these parameters are provided in Table 1.

The different network performance parameters are used to compare the relative performance values of the proposed algorithm. The considered performance parameters are the mean candidate $s-t$ QSS paths, average hop count, and average energy efficiency. The mean candidate $s-t$ QSS paths parameter indicates the mean number of candidate optimal $s-t$ reliable and quickest paths for the data services. The average hop count is a performance measure used for calculating the energy efficiency. If the average hop count decreases, the average energy efficiency increases. The energy efficiency parameter indicates efficiency of energy use for data transmission services. The energy efficiency is the ratio of the amount of data traffic transferred to the total energy consumed for the data transmission across the $s-t$ paths. The unit for energy efficiency is bits/s/J. The unit of

Table 1 Values of different parameters for random experiment

S. No.	List of parameters	Set of parameter values
1	Number of nodes	100, 200 and 300
2	Number of links	4600, 18,500 and 41,500
3	Number of distinct capacities	10,100 and 1000
4	Different data traffic	1and 10 Mb
5	Different energy associated with nodes	10, 100 and 100 J
6	Different SLAs assigned for the service	100, 110 and 120 s

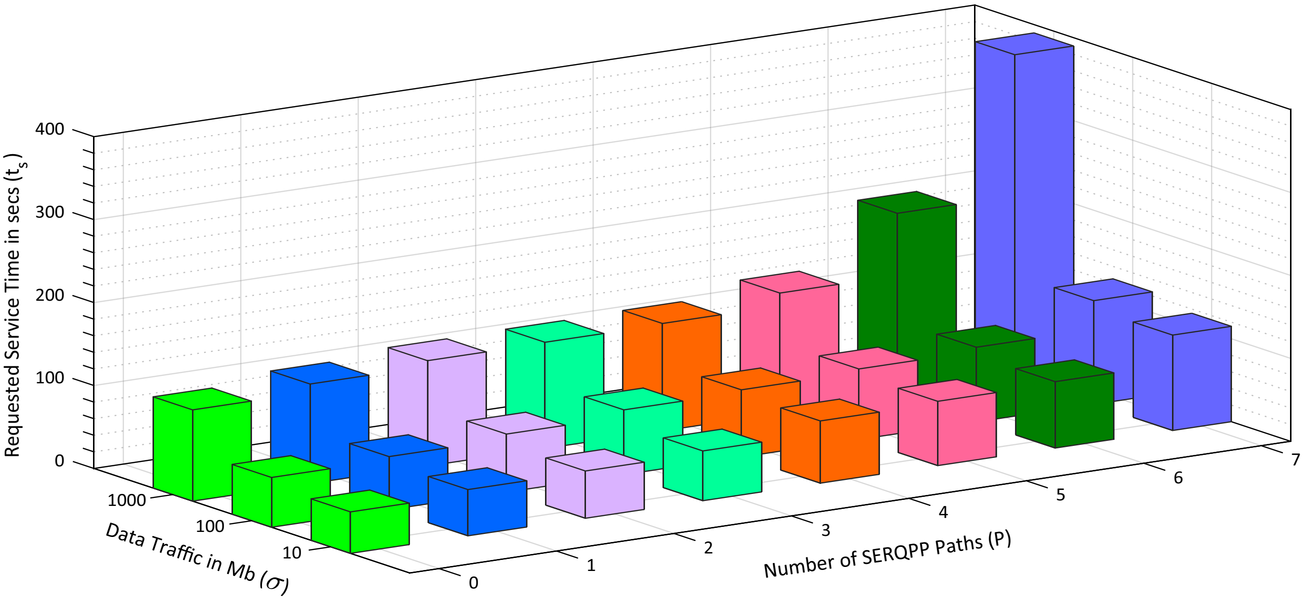

Fig. 7 Pattern of the SERQPP cooperative paths for different data amounts (σ) and service times (t_s)

data is taken as Mb. Therefore, the units for energy efficiency are taken as Mb/s/J.

5.2 Discussion

The results for the standard network and random networks are provided in the following subsections.

5.2.1 Standard Topology

The number of distinct capacities present in the network is determined from the algorithm, and the subnetworks are formed. Every link of the network is sorted with the label of minimum SLA energy cooperative capacity. The $s - t$ paths are found from the different subnetworks by using the cost metric in Eq. (6), and the QSS is determined using Eq. (19). Finally, the $s - t$ path with the minimum cost is obtained from the QSS.

The results are simulated for 1000 random iterations. The average number of distinct capacities and QSS is 22.1 and 6.6, respectively. The average capacity and hop count for the minimum-cost $s - t$ path from the QSS are 16.7 Mb/s and 7.1 hops, respectively. The average energy efficiency required in data transmission is calculated by dividing the capacity with the total energy consumed in the transmission of σ units of data. The calculated average energy efficiency is 3.46×10^5 bits/s/J.

The results with different values of σ and t_s are displayed in Fig. 7. The considered values of data are 100, 1000, and 10,000 Mb. The requested service time (t_s) is varied over 0–400 s to obtain the SERQPP QSS paths. For a small amount of data and low requested service time, the number of SERQPP QSS paths is limited. However, the number of the SERQPP paths increases as the value of the requested service time increases. Therefore, to satisfy the SERQPP path energy, the data amount and SLA are important factors.

5.2.2 Waxman Random Network Topology

The first to third columns of Tables 2–4 indicate the changes in the capacities, nodes, and links of the networks, respectively. The deviation in the mean number of candidate $s - t$ QSS routes, average hop count, and average energy efficiency is presented in Tables 2–4, respectively, for 1 Mb of data. The

Table 2 The mean candidate $\mathbf{s-t}$ QSS path for the SERQPP algorithm to transmit 1 Mb data

r	n	m	Mean candidate $s-t$ QSS path for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	6.4	7.7	7.9	9.1	9.4	9.5	9.5	9.7	9.8
	200	18,500	9.1	9.4	9.5	9.2	9.5	9.7	9.5	9.5	9.8
	300	41,500	8.5	9.1	9.5	8.6	9.2	9.5	8.9	9.2	9.5
100	100	4600	38.2	47.5	54.8	54.5	62	63.9	59.2	63.8	65.2
	200	18,500	46.3	53.2	53.9	55.1	60	64.4	61.8	62.1	63.5
	300	41,500	49.2	53.1	62	61	65.2	65.3	59	61.2	61.8
1000	100	4600	82	86.5	88	89.2	97.1	98.5	86	93.3	99
	200	18,500	86	87.2	90.1	88	97.5	98.9	83.2	86	87.2
	300	41,500	83	94.2	95.6	96.6	98	99.2	92.2	98.2	98.5

Table 3 Average hop counts for the optimal path for the SERQPP algorithm to transmit 1 Mb data

r	n	m	Average hop counts for the optimal path for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	1.9	1.9	1.7	1.5	1.3	1.2	1.6	1.4	1.4
	200	18,500	1.5	1.3	1.2	1.6	1.4	1.3	1.8	1.7	1.7
	300	41,500	1.8	1.7	1.7	1.5	1.2	1.2	1.8	1.7	1.6
100	100	4600	1.5	1.4	1.4	1.8	1.8	1.6	1.5	1.4	1.4
	200	18,500	1.5	1.5	1	1.2	1	1	1.2	1	1
	300	41,500	1.8	1.5	1.2	1.9	1.6	1.2	1.4	1.3	1.4
1000	100	4600	1.5	1.2	1.2	1.5	1.2	1.2	1	1	1
	200	18,500	1.5	1.4	1.4	1.2	1.2	1	1.5	1.2	1.2
	300	41,500	1.5	1.5	1.4	1.2	1.1	1.1	1.4	1.3	1.3

results obtained in this study have a confidence level of 95% and error of 5%.

Table 2 indicates the results for the variation in the available energy and SLAs. The results in columns 4, 5, and 6 for the available energy indicate that the number of selected mean candidate $s-t$ QSS paths increased as the SLA requested service time increased from 100 to 120 sec. Thus, the SLA requested service time is the criterion to sort the SLA cooperative links for critical and continuous data transmission. The usefulness of the mean candidate $s-t$ QSS paths parameter lies in the fact that it assures successful data transmission if any of the links in the CNN fail. Moreover, a high number of the aforementioned parameter is favorable for critical healthcare applications.

For a fixed SLA requested service time (t_s), the energy available at each node varies from 10 to 1000 J. From Table 2, in columns 4, 7, and 10, the number of selected mean candidate $s-t$ QSS paths increases to 6.4, 9.1, and 9.5, respectively. Thus, the energy available at the nodes is also a key factor for selecting a high number of mean candidate $s-t$ QSS paths. The remainder of the table exhibits the same variation with respect to the SLAs and energy. The number of distinct capacities and nodes plays an important role in selecting the mean number of $s-t$ QSS paths. If the distinct capacities and number of nodes are increased, the mean number of selected $s-t$ paths also increases, which is favorable for the criticality and continuity of data transmission.

Table 3 indicates that when the SLA values and energy available at the nodes are increased, the hop count of the selected minimum-cost $s-t$ path decreases. The usefulness of this performance measure is that if the numbers of hops are decreased, the energy available at the nodes is efficiently used. Moreover, this measure is useful for security. However, in this study, this constraint is not considered. As presented in columns 4, 5, and 6 of Table 3, the number of average hop counts decreases with an increase in the SLA requested service time. The same trend is observed in columns 4, 7, and 10 if the energy available at the nodes is increased from 10 to 1000 J. The minimum hop count enables data transmission with the lowest possible time.

Table 4 Average energy efficiency for the optimal path for the SERQPP algorithm to transmit 1 Mb data

r	n	m	Average energy efficiency for the optimal path for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	0.48878	0.85057	1.80913	0.15515	0.17311	0.18467	0.0568	0.4416	2.0408
	200	18,500	0.1998	0.8264	0.904	0.0104	0.193	0.3086	0.0657	0.185	0.5264
	300	41,500	0.1174	0.2085	0.3356	0.0111	0.2066	0.25	0.0178	0.0152	0.6944
100	100	4600	1.0649	2.1009	3.5625	0.0112	0.0331	0.0356	0.0026	0.6944	2.7778
	200	18,500	0.571	0.8547	1.3086	0.0625	0.0952	1.05684	0.0204	0.0772	0.0816
	300	41,500	1.5944	1.6235	2.2268	0.0116	0.0204	0.0204	0.0316	0.0435	3.1724
1000	100	4600	0.2066	0.6969	0.7223	0.277	0.0142	0.0693	0.0132	0.0865	0.8264
	200	18,500	0.1155	0.1668	0.3364	0.0152	0.189	0.26	0.0408	0.8148	1.0754
	300	41,500	0.8264	1.189	3.52	0.4444	1.176	1.5917	0.2268	0.8264	0.9945

Table 5 Mean candidate $s - t$ QSS path for the SERQPP algorithm to transmit 10 Mb data

r	n	m	Mean candidate s − t QSS routes for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	6.4	7.7	7.9	9.1	9.4	9.5	9.5	9.7	9.8
	200	18,500	9.1	9.4	9.5	9.2	9.5	9.7	9.5	9.5	9.8
	300	41,500	8.5	9.1	9.5	8.6	9.2	9.5	8.9	9.2	9.5
100	100	4600	38.2	47.5	54.8	54.5	62	63.9	59.2	63.8	65.2
	200	18,500	46.3	53.2	53.9	55.1	60	64.4	61.8	62.1	63.5
	300	41,500	52.2	55	57.5	55.2	58	58.6	60	61.9	65.3
1000	100	4600	82	86.5	88	89.2	97.1	98.5	86	93.3	99
	200	18,500	86	87.2	90.1	88	97.5	98.9	83.2	86	87.2
	300	41,500	98.2	100.1	101.9	100.1	105.2	108.7	103	106.5	110.7

Table 6 Average hop counts for the optimal path for the SERQPP algorithm to transmit 10 Mb data

r	n	m	Average hop counts for the optimal path for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	1.9	1.9	1.7	1.5	1.3	1.2	1.6	1.4	1.4
	200	18,500	1.5	1.3	1.2	1.6	1.4	1.3	1.8	1.7	1.7
	300	41,500	1.8	1.7	1.7	1.5	1.2	1.2	1.8	1.7	1.6
100	100	4600	1.5	1.4	1.4	1.8	1.8	1.6	1.5	1.4	1.4
	200	18,500	1.5	1.5	1	1.2	1	1	1.2	1	1
	300	41,500	1.5	1.2	1.1	1.3	1.1	1.1	1.1	1.1	1
1000	100	4600	1.5	1.2	1.2	1.5	1.2	1.2	1	1	1
	200	18,500	1.5	1.4	1.4	1.2	1.2	1	1.5	1.2	1.2
	300	41,500	1.6	1.4	1.3	1.5	1.3	1.3	1.3	1.1	1.1

Another important performance measure is the energy efficiency (Mb/s/J). Table 4 is used to determine the importance of the variation in the SLAs and available energy. Columns 4, 5, and 6 in Table 4 indicate that when the SLA requested service time (t_s) is increased, the average energy efficiency also increases. The energy efficiency is also increased if we increase the value of energy for a fixed value of the SLA requested service time. The same trend can be

Table 7 Average energy efficiency for the optimal path for the SERQPP algorithm to transmit 10 Mb data

r	n	m	Average energy efficiency for the optimal path for 10 runs								
			$P_u = 10$			$P_u = 100$			$P_u = 1000$		
			$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$	$t_s = 100$	$t_s = 110$	$t_s = 120$
10	100	4600	0.48878	0.85057	1.80913	0.15515	0.17311	0.18467	0.0568	0.4416	2.0408
	200	18,500	0.1998	0.8264	0.904	0.0104	0.193	0.3086	0.0657	0.185	0.5264
	300	41,500	0.1174	0.2085	0.3356	0.0111	0.2066	0.25	0.0178	0.0152	0.6944
100	100	4600	1.0649	2.1009	3.5625	0.0112	0.0331	0.0356	0.0026	0.6944	2.7778
	200	18,500	0.571	0.8547	1.3086	0.0625	0.0952	1.05684	0.0204	0.0772	0.0816
	300	41,500	0.5206	1.484	1.9582	0.281	0.2491	1.2012	0.0109	0.0149	0.0244
1000	100	4600	0.2066	0.6969	0.7223	0.277	0.0142	0.0693	0.0132	0.0865	0.8264
	200	18,500	0.1155	0.1668	0.3364	0.0152	0.189	0.26	0.0408	0.8148	1.0754
	300	41,500	0.0118	0.4521	1.2854	0.254	1.0254	1.5921	0.6251	0.9952	1.298

observed if we increase the number of distinct capacities and number of nodes. Some results may not follow the trends because the statistical results have 5% error.

The results for different data traffics are also examined. Tables 5–7 present the results of the variation in the mean number of candidate $s - t$ QSS routes, average hop count, and average energy efficiency for a data traffic of 10 Mb. The same trends described in the aforementioned text are followed for the variation in the amount of data transmitted from the source to the destination. The results for the transmission of 10 Mb data are presented in Tables 5–7.

The aforementioned results depict the usefulness of the proposed algorithm with respect to SLAs and energy for supporting critical healthcare applications. The variations in SLAs and energy are important for critical healthcare services. However, if the data traffic increases, the performance measures exhibit decreased values because a large amount of energy and time are required to support a large amount of data. Sometimes, the values of the requested SLAs and endowed energy are insufficient for data transmission. The values of SLAs and energy can be increased to favor high values of data transmission for the criticality and continuity of service. If the service criticality is a prime constraint and cannot be compromised over other conditions, then other mediums, such as green corridors and dedicated networks, must be used for the completion of service.

5.3 Comparison

The proposed algorithm is qualitatively compared with various existing algorithms, as presented in Table 8. Table 8 indicates that the proposed SERQPP algorithm considers both SLA and energy cooperation.

The positive tick (✓) indicates that the model is incorporated, whereas the negative tick (×) indicates that the model is not incorporated. Table 8 indicates that the SERQPP algorithm outperformed the existing algorithms with the same time complexities.

Table 8 Qualitative comparison of the existing algorithms with the proposed algorithm

Algorithm	Quickest	Reliable	Energy	SLA
Chen and Chin [46]	✓	×	×	×
Xue [34]	✓	✓	×	×
Lin [36]	✓	✓	×	×
Calvete [37]	✓	✓	×	×
Calvete [19,21]	✓	×	✓	×
Sharma [57]	✓	✓	×	×
Proposed SERQPP	✓	✓	✓	✓

To show the quantitative comparison of the proposed algorithm with exiting algorithms in the literature, we have opted the standard topology as shown in Fig. 6. The link metrics and other associated parameters have been generated randomly from the uniform distribution as shown in Table 9.

We have compared our proposed algorithm with Chen and Chin [46], Calvete [37], and Calvete [19] to transmit 100 Mb data from s to t.

Using Chen and Chin [46], the quickest path is formed as $1-6-9-12-13-14-18-24$ having the path capacity $c(P) = 14$ Mb/s. However, this algorithm is unable to comment on reliability of the path. Also, the problem objective of Chen and Chin [46] is not aware of reliability, SLAs, and energy.

In 2012, Calvete [37] proposed an algorithm to find the data transmission path for reliable and quickest path problem (RQPP) having a threshold value of (α). Let here $-\ln(\alpha)$ is considered as 8.4593 to find the path for RQPP. The proposed algorithm in this paper gives the RQPP path as $1-6-7-8-10-13-14-18-24$ having path capacity $c(P) = 34$ Mb/s.

Table 9 Data values for 24-node USANET associated with each link

Link	$d(u, v)$	$c(u, v)$	$r_l(u, v)$	$\omega(u, v)$	Link	$d(u, v)$	$c(u, v)$	$r_l(u, v)$	$\omega(u, v)$
a_1	14	93	0.1389	0.0588	a_{23}	9	99	0.0890	0.0891
a_2	42	53	0.4154	5.9976	a_{24}	66	87	0.6552	21.7800
a_3	30	53	0.3050	6.4800	a_{25}	6	49	0.0589	0.0504
a_4	19	14	0.1897	0.5054	a_{26}	55	37	0.5534	20.2675
a_5	61	57	0.6072	24.5586	a_{27}	15	25	0.1472	1.1025
a_6	6	19	0.0648	0.0396	a_{28}	34	49	0.3418	3.9304
a_7	37	67	0.3704	7.8033	a_{29}	17	57	0.1663	1.5028
a_8	99	11	0.9883	65.6667	a_{30}	20	49	0.1998	0.7600
a_9	44	67	0.4418	12.7776	a_{31}	44	18	0.4442	8.5184
a_{10}	63	52	0.6299	5.5566	a_{32}	96	25	0.9580	31.3344
a_{11}	55	87	0.5527	16.0325	a_{33}	17	97	0.1703	0.4046
a_{12}	58	96	0.575	24.2208	a_{34}	41	52	0.4116	11.0946
a_{13}	17	25	0.1739	0.7225	a_{35}	54	53	0.5396	26.2440
a_{14}	17	87	0.1708	0.5202	a_{36}	72	42	0.7181	9.3312
a_{15}	15	42	0.1536	2.0925	a_{37}	77	66	0.7709	55.7326
a_{16}	89	50	0.8903	38.8129	a_{38}	34	25	0.3402	8.3232
a_{17}	63	50	0.6252	14.6853	a_{39}	52	93	0.5221	6.7600
a_{18}	40	3	0.3972	5.4400	a_{40}	10	42	0.0954	0.5200
a_{19}	73	52	0.7349	35.7043	a_{41}	88	2	0.8768	13.9392
a_{20}	100	53	0.9994	99.0000	a_{42}	95	87	0.9477	45.1250
a_{21}	42	42	0.4222	0.5292	a_{43}	66	97	0.6566	10.8900
a_{22}	52	67	0.5221	5.1376					

Table 10 Qualitative comparison of the existing algorithms with the proposed algorithm

Algorithm	Objective Function	Path	Path capacity	Remark
Chen and Chin [46]	$\min_{p} T_\sigma(P)$ s.t. P is an $s - t$ path in the network G	$1-6-9-12-13-14-18-24$	14 (Mb/s)	Quickest Path Problem (QPP)
Calvete [37]	$\min_{p} T_\sigma(P)$ $R(P) \geq \alpha$ s.t. P is an $s - t$ path in the network G	$1-6-7-8-10-13-14-18-24$	34 (Mb/s)	Reliable Quickest Path Problem (RQPP)
Calvete [19]	$\min_{p} T_\sigma(P)$ $P_u(\sigma, P) \geq 0, u \in P$ s.t. P is an $s - t$ path in the network G	$1-6-9-12-13-14-18-24$	14 (Mb/s)	Energy-constrained Quickest Path Problem (EQPP)
Proposed SERQPP	$\min_{p} \{-\ln [R_T(P)]\}$ s.t. $r_u(\sigma, P) \geq 0, u \in P$ $P_u(\sigma, P) \geq 0, u \in P$ P is an $s - t$ path in network G	$1-6-9-12-16-17-23-24$	25 (Mb/s)	SLA Energy-Aware Reliable Quickest Path Problem (SERQPP)

However, again in this algorithm no attention was paid toward SLAs and energy.

Later, in 2017 H. Calvete [19] proposes an algorithm by considering the sufficient amount of energy available at nodes (i.e., P_u) of $3 \times \sim 10^7$ J. Therefore, by using EQPP algorithm proposed in this paper computed the path as $1-6-9-12-13-14-18-24$ having the path capacity $c(P) = 14$ Mb/s. Although the path opted for data transmission is same as the path computed by Chen and Chin [46], but this path is capable of successful data transmission along a path with the complete knowledge of available energy at nodes. However, in this algorithm again no attention was given to SLAs.

In this study, in the proposed SERQPP algorithm the SLAs are considered as given in the above Sect. 5.1.1 to compute the path. By using the SERQPP algorithm the path is computed as $1-6-9-12-16-17-23-24$ having the path capacity $c(P) = 25$ Mb/s. In this algorithm, energy and SLAs have been satisfied for the data transmission. All these quantitative results are shown in Table 10.

Here, one main point has to be noted that the link reliability and the constraints have a strong influence on the computation of a path. The above quantitative comparative study shows that the computation of quickest paths sometime computes the quickest path. However, this behavior has no harm to the e-healthcare application such that as link reliability is also equally important as the minimum transmission time.

6 Conclusion

In this paper, a generalized SERQPP model with the delay, reliability, energy, and SLA parameters is proposed. The mathematical analysis and numerical results are illustrated using the standard topology and random topologies. The novelty of the proposed model relies on the reliable and QPP path computation, which allows the SLA energy cooperative QSS to be used for critical healthcare applications. The results obtained for QSS paths with different values of requested service time and data traffic indicate that values of the SLAs and energy play an important role in the selection of the SLA energy cooperative data transmission path. The other considered performance measures are the average hop count and average energy efficiency, which strengthen the applicability of the proposed algorithms in mission critical applications. The conclusion can be summarized from this study as:

- The average number of selected $s-t$ QSS paths increases when the SLA requested service time (t_s) and energy available at the nodes are increased. Thus, if we obtain a high number of paths, the possibility of receiving assured data transmission increases when any breakdown occurs in networks.
- The aforementioned trend is also applicable to the number of distinct capacities. The number of nodes increases, which is favorable for critical and continuous data transmission services.
- The average energy efficiency increases as the SLA and available energy values increase. Therefore, for a high amount of data traffic, a network with high values of SLAs and energy is suitable for data transmission. The increased energy efficiency is suitable for the long-term usability of networks.

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