Quality of Information with Minimum Requirements for Emergency Communications

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Abstract

In emergency situations like the recent Australian bushfires, it is crucial for civilians and firefighters to receive critical information such as available escape routes with guarantees on accuracy, timeliness, reliability, and completeness. Mobile Ad-hoc Networks (MANETs) can provide communications in bushfires but guaranteeing information delivery that meets user needs is not easy with current MANET forwarding solutions. Quality of Information (QoI) based source selection has recently been developed in MANETs for this purpose. The most popular QoI scheme uses the analytic hierarchy process (AHP), an intensive pairwise comparison procedure to score sources using a linear combination of low-level network metrics in a hierarchical two-step process. Current QoI-AHP, by directing traffic to a single high scoring source, often creates additional bottlenecks and does not guarantee the higher-level information needs of users. In this work, we develop a novel low overhead source selection scheme, QoI with Thresholds (QoIT), that is designed to deliver the required target performance thresholds for users. QoIT introduces two modifications to QoI-AHP. Firstly, it replaces the raw network performance value by the ratio of the network metric value to the user's demand for that performance, a goodness measure of how far the value of the network metric is from meeting the user's demand. The ratios are fed into QoIT's pro-

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cess for assigning multi-dimensional scores to each source. Secondly, QoIT uses new source selection criteria to choose the source that best delivers the information that meets the user needs. To evaluate QoIT and QoI-AHP performances in emergency communications, we develop a novel simulation software with realistic models across multiple network layers. Our QoIT algorithm works with any combination of quality thresholds for any subset of network metrics. Simulation results show that QoIT out-performs QoI-AHP by increasing user usability by 57%, ensuring high priority requirements are met, reducing source bottlenecks, and decreasing the source selection time by 62.5%.

Keywords: QoI, QoS, MANETs, Bushfire Communications, User Requirements

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1. Introduction

The devastating bushfires in the Australian summer of 2019/20 caused significant social and economic damage in the populated country and coastal regions. During the bushfires and other similar disaster situations like flooding and earthquake, maintaining a functional emergency communication network is crucial for saving lives and properties [1]. Bushfires move rapidly and often destroy telecommunication infrastructure that people rely on for emergency information. When cellular and satellite services are unavailable, setting up a Mobile Ad-hoc Network (MANET) is a potential solution for creating a communication network [2]. As an example of this, groups of campers have established ad-hoc networks in remote locations using the goTenna technology [3]. These networks in remote locations have been used to increase their safety and assist with social communications.

This paper looks at the possible applications of such networks to relay information in emergency situations. However, recent experience with Australian bushfires has shown that not all information is equal. For example, the report in [4] suggests that during dangerous bushfires, information about safe sheltering points and escape routes must be delivered in a timely fashion to users with precise and trusted location data to avoid fatalities. Current MANET routing solutions do not focus on these information requirements. Rather they mostly concentrate on low-level network metrics such as hops count, bandwidth, and delay.

One approach for differentiating information sources is to use the Quality of Information (QoI) [5–10]. The most common solution is QoI with

the analytic hierarchy process (QoI-AHP) [11] that linearly combines the low-level network metrics including bandwidth, hops count, path-integrity, and information-utility to produce the higher-level information quality metrics such as completeness, accuracy, reliability, and timeliness. Information metrics are then combined using quality-metric based adaptive weights to produce a single aggregated QoI score of a source. However, by using the aggregate high-level QoI scores, QoI-AHP often selects sources that do not meet user requirements on individual network or quality metrics [12]. Furthermore, in QoI-AHP, a source may repeatedly produce the highest QoI-score, even after updating the link characteristics on the assigned paths from the source to multiple querying nodes. This is when static information quality attributes such as information accuracy or reliability (which are independent of bandwidth availability) contribute with high individual scores towards the aggregated QoI score. This often results in directing all the traffic to the same source node, hence creating new bottlenecks in the network. Another significant issue with QoI-AHP is the AHP's intensive computation requirement. A user node needs to perform $O(n^2/2)$ pair-wise comparisons in every source selection round to determine the best source, with n being the number of available source nodes [13].

In this paper, we propose a novel scheme, QoI with Thresholds (QoIT), to address the issues with QoI-AHP. QoIT introduces two modifications to AHP. First, it replaces the raw network performance value by a measure of "goodness" that shows how closely the metric value meets the user demand. The "goodness" of each network metric is generally the ratio between its measured value and its target value. With goodness measure, all the source nodes that meet the defined thresholds are treated similarly, thus avoiding excessive load on a single source node. Secondly, instead of intensive pair-wise comparisons, QoIT follows a simpler hierarchy of selection criteria to select the source best meeting the thresholds. Our novel selection hierarchy composes four criteria that select a source by sequentially assessing (i) whether all the quality needs of an application meets, (ii) the aggregated priority of quality needs that successfully meet, (iii) the number of quality needs that successfully meet, and finally (iv) the extent to which a source meets different quality needs.

There is a wide array of MANETs simulation tools, such as NS3 [14] and Omnet++ [15]. However, none of these tools offers native support for the application's Quality of Information (QoI), especially in Bushfire emergencies. For fast prototyping, we develop a lightweight and easy to use simulation

software focusing on QoI in emergency communications with realistic but simplified physical, MAC, routing, and application layer models. We use our simulator to evaluate the performance of QoIT and QoI-AHP in emergency situations. Simulation results show that QoIT achieves a 57% gain in user usability and out-performs QoI-AHP in fulfilling higher priority requirements. QoIT also decreases the source selection time by 62.5%, a desirable feature for wireless nodes with limited processing power. Moreover, QoIT ensures that a high number of quality metrics are satisfied with reduced source bottlenecks.

Our main contributions in this paper are:

- proposing a novel low overhead Quality of Information algorithm for MANETs that explicitly considers the user requirements in selecting an optimal source, to relay information in emergency situations, while avoiding new source bottlenecks; and
- developing an easy-to-use simulation tool with realistic models across multiple layers for studying QoI based MANETs in emergency situations. The simulation software includes the implementation of the QoI-AHP and QoIT solutions and is publicly available to facilitate further research in this important area[1].

The paper has five sections. After discussing the existing solutions for QoI-based source selection in Section 2, we review the issues with the current QoI-AHP method and motivate our proposal of QoIT in Section 3. We provide the details of QoIT in Section 4. In Section 5, we describe our experimental setup for MANETs in bushfire scenarios and evaluate the proposed solution in comparison to the baseline method of QoI-AHP under various network use-cases. Lastly, we discuss the limitations of our work in Section 6 and conclude the paper in Section 7.

2. Related Work

2.1. Quality of Information (QoI) and Analytical Hierarchy Process (AHP)

QoI, also known as Value of Information (VoI), is a recent approach used in networking where network metrics are combined to measure the value of information, which is then used to decide node level forwarding decisions [5–7, 9, 10]. In QoI, network layer quality of service (QoS) attributes such as hops count, loss rate, bandwidth, and delay are evaluated to determine their role in the fulfillment of high-level features such as integrity, reliability,

[1] `http://github.com/AmeerShakaybArsalaan/QoIT.git`

relevance, freshness, completeness, provenance, timeliness and accuracy of the required information. The high-level requirements vary based on the operational context and application demands.

QoI has been proposed to be used in MANETs and wireless sensor networks for managing information flows [16]. QoI-aware networking is integrated into tactical network design for exploring provenance tracking and extracting credible information [5]. In information theory "Age of information", a related concept, is actively studied [17] to assess the freshness and accuracy of the information. Recently, the authors in [7] study a network's performance, scalability, and its limitation by modeling various network delay contributors in relation to QoI needs.

The concept of the analytic hierarchy process (AHP) was proposed by Satty [18] to analyze complex decisions in Mathematics and Psychology. AHP was used in QoI-aware networking [11] to assist in multi-criteria decision making for selecting a data delivery path. The information metrics used in [11] include completeness, accuracy, reliability, and timeliness. To calculate information metrics from network layer metrics, QoI-AHP performs pair-wise comparisons of the network attributes for all sources. The results of these comparisons are fed into the calculation of quality metric scores, which are then linearly combined to produce an overall QoI score of a source.

The source is chosen based on the highest QoI score of QoI-AHP; however, this does not guarantee that the selected source can meet all quality needs [12]. Often the chosen source has more than the required performance metric value of one type but lacks another type. Moreover, applications may also have a certain level of network performance requirements to be able to produce useful information for users. The studies in [19–24] illustrate the QoS needs of different applications, summarized in Table 1. In emergency networks, when life-saving decisions are made upon the received information, the specification of required quality features for the information and their fulfillment becomes vital.

2.2. Quality of Service Routing in Ad hoc Networks

A related area of research is Quality of Service (QoS) based routing [25–29] in ad hoc networks with a number of surveys [30–37]. In these works, the selection of forwarding paths was based on one or more QoS requirement(s) such as delay, bandwidth, length, stability, and reliability of communication paths. To minimize the end-to-end delay, packet loss, and to save network energy, the studies presented in [28, 29, 38, 39] propose the use of queuing delay

Traffic Class	QoS Metrics			
	Delay (ms)	Jitter (ms)	Bandwidth (bps)	Error Rate
Web Browsing	<400	NA	<30.5K	0
Enhanced Web Browsing	<400	NA	<24K	0
Email	Low	NA	<10K	0
SMTP, FTP, Telnet	<250	NA	<1K	0
Audio/Video Broadcasting	<150	100-150	28.8K-1.5M	<0.001% - 0.1%
Interactive Audio/Video on Demand	<150	100-150	28.8K-1.5M	<0.001% - 0.1%
Audio/Video Conferencing	<150	<400	8K-2M	<0.01% - 1%
Audio-graphics Conferencing	<150	<400	9.6K-19.6K	<1%
Video-Phony	<100	<400	80K-2M	<0.01%
VoIP	<100	<400	8K-80K	<1%

Table 1: QoS needs for different applications.

and positions of relay nodes to decide optimal routes in ad hoc networks. QoS based OLSR optimization is considered in [40] to compute and maintain the shortest-widest paths in terms of delay and throughput, whereas by [41] to reduce the delay in highly mobile VANETs using Ant Colony Optimization. Costa et al. [42] use a series of OLSR optimization algorithms to optimally select a route based on bandwidth, propagation delay, and link loss probability metrics. Korkmaz et al. [43] propose a routing protocol for real-time traffic in VANETs to provide delay bounded throughput guarantees.

Other studies aim to select stable and reliable paths using QoS based routing decisions. For example, Eiza et al. [44] propose a routing algorithm that picks the route satisfying constraints on link failure risk and packet delivery ratio to ensure reliable data transmission in VANETs. Reliable transfer of messages across the forwarding paths is also proposed in [25, 26] that use QoS based decisions to reduce congestion. To guarantee reduced packet losses and fast response time, a mechanism is applied on OLSR [45] that uses the relative mobility of nodes to its neighbors to establish stable and sustainable paths in MANETs. Similarly, [46] presents a QoS-OLSR based clustering protocol for VANETs to maintain communication stability with reduced link failures and improved packet delay and delivery ratio.

The above studies focus on the QoS constraints that address the performance issues at the network, MAC, and physical layers. However, they do not consider the contributions of lower layer metrics toward users' satisfaction at the application layer, which is the goal of this study. Arsalaan et al. [12] compared QoS and QoI-AHP [11] based routing under various realistic MANET settings and found that QoS-based solution performs well when a single network metric is of significance to the task, whereas a QoI-AHP based decision proves a better choice when the task requires fulfillment of

multiple QoS needs. Our work in this paper focuses on high-level aggregate information rather than individual network metrics as in QoS routing.

3. Problem Definition

In this section, we explain the working of QoI-AHP for source selection and identify its associated issues, with the help of an example network shown in Figure 1. These issues provide the basis for the problem we aim to solve in this work. The example network consists of a user node U, eleven sources nodes $S = \{s_1, ...s_{11}\}$, ten relay nodes $R = \{1, ..., 10\}$, and thirty two bi-directional links. The source nodes carry the same information but with varying quality. Each link represents the tuple $link(bandwidth, link\text{-}integrity)$, where link integrity is the strength of the encryption deployed on the links. Routes between end-nodes are established using Dijkstra's shortest path algorithm, where the weight of a link is equal to the inverse of the data rate on the link. Moreover, each source node in the example network has an information utility value (listed next to each source). Node U selects one source out of the nodes in S to receive information.

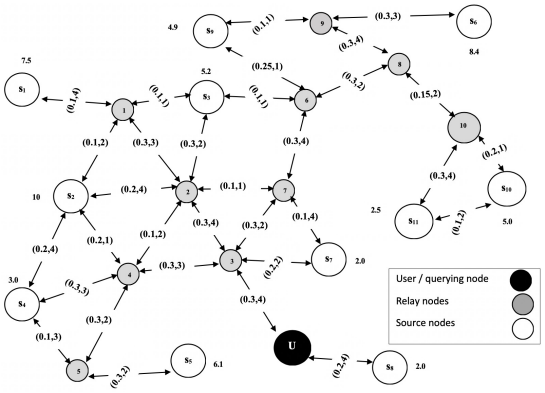


Figure 1: An example network with a single querying node and multiple source nodes.

3.1. Network Metrics Values and Thresholds

We consider four network metrics, as discussed in [11]. They are hops count (HC), available bandwidth (BW), information utility (IU), and path integrity (PI). Bandwidth and hop count are standard network metrics that are used widely in MANET routing. The source information utility score indicates the objective value of data to the querying node and is computed as the percentage of times the required information is successfully communicated within an established time frame. Path integrity indicates how secure

the links along the path are for data transmission. We assume a set of 4 keys i.e., 32-bit, 64-bit, 128-bit, and 256-bit traffic encryption, which for simplicity is represented in our simulation by key-ID 1, 2, 3, and 4 respectively. Each node is randomly assigned one of the given key lengths. We measure link integrity as the minimum strength of the keys held by a link's adjacent nodes, whereas path integrity is the minimum of link integrity along the path. For the example network in Figure 1, Table 2 shows the value v_j for each network metric $j \in [BW, HC, IU, PI]$ contained on the path from each $s \in S$ to U.

Each application needs certain network layer resources to achieve the desired performance. We use a threshold t_j to indicate the minimum required quantity and quality of a network resource j by a given application. The thresholds are assumed to be $[t_{BW}, t_{HC}, t_{IU}, t_{PI}] = [0.3, 3, 5, 2]$ for the application in the example network.

Source	**Network Metric Value**			
	v_{BW}	v_{HC}	v_{IU}	v_{PI}
s_1	0.1	4	7.5	3
s_2	0.2	3	10.0	4
s_3	0.3	3	5.2	2
s_4	0.3	3	3.0	3
s_5	0.3	4	6.1	2
s_6	0.3	6	8.4	2
s_7	0.2	2	2.0	2
s_8	0.2	1	2.0	4
s_9	0.25	4	4.9	1
s_{10}	0.15	6	5.0	1
s_{11}	0.15	6	2.5	2

Table 2: The network metric values (on paths) from source nodes.

3.2. QoI-AHP based Pre-processing of Network Metrics Values

Before computing source information score, AHP uses five pre-processing steps to process the network metrics values, details of which can be found in [11] and summarized in Appendix A. At the end of the pre-processing steps, a priority vector p is generated where each entry p_j stores the relative priority of a source in comparison to other source nodes for metric j. For example, the p_{BW} value of s_1 in Table 3 is the average of s_1 row elements from Table A.4. The alternate priority vector with respect to each network metric, for the example network, is shown in Table 3. The pre-processing steps constitute an important role in assigning a source node to a user; however, it increases the computational cost of the method by going through all the steps each time a change in the network state occurs.

Source	Alternate Priority Vector			
	p_{BW}	p_{HC}	p_{IU}	p_{PI}
s_1	0.015928	0.056086	0.15228	0.118221
s_2	0.049076	0.100888	0.29048	0.246552
s_3	0.173928	0.100888	0.069424	0.046393
		...		
s_{11}	0.024279	0.017225	0.022332	0.046393

Table 3: Alternate priority vector for all network metrics.

3.3. QoI-AHP based Quality Metrics Values

The next step is to compute the quality metric values for each source using the corresponding priority values from Table 3. A quality metric can be influenced by multiple network metrics and a network metric can impact multiple quality metrics. The quality metrics we consider in this work are:

- *Accuracy* (A): implies information correctness and its relevance to accomplishing a task. It ensures that information does not contain the wrong information. The value of accuracy V_A is the sum of the product of contributing network metrics priority values with their corresponding weights. In Equation (1), p_{PI} and p_{IU} indicate the priority values of path integrity and information utility, while $w_{A\text{-}PI}$ and $w_{A\text{-}IU}$ are their corresponding weights towards accuracy.
$$V_A = (p_{PI} * w_{A\text{-}PI}) + (p_{IU} * w_{A\text{-}IU}) \quad (1)$$
- *Reliability* (R): is the degree of the readiness of the source to be available to provide information when requested and includes the trustworthiness and integrity of the information provided. The value of reliability V_R is evaluated using the weighted sum of the priority values of path integrity p_{PI} and hop count p_{HC}.
$$V_R = (p_{PI} * w_{R\text{-}PI}) + (p_{HC} * w_{R\text{-}HC}) \quad (2)$$
- *Completeness* (C): indicates the ability to receive the relevant and critical information intact within the desired time frame. The value of completeness V_C is calculated as the weighted sum of the priority values of bandwidth p_{BW} and information utility p_{IU}.
$$V_C = (p_{BW} * w_{C\text{-}BW}) + (p_{IU} * w_{C\text{-}IU}) \quad (3)$$
- *Timeliness* (T): refers to the ability to respond to a query within the required time constraints. It is computed by the rate at which the querying user receives the information, depending on path links and hops count. The value of timeliness V_T is calculated as the weighted sum of the priority values of bandwidth p_{BW} and hop count p_{HC}.
$$V_T = (p_{BW} * w_{T\text{-}BW}) + (p_{HC} * w_{T\text{-}HC}) \quad (4)$$

The weights $w_{i\text{-}j}$ indicate the importance of a particular network metric

j towards a specific quality attribute i and are typically chosen by the users based on previous experience. For simplicity, in our example, we assume the same weight for each network metric towards its corresponding quality metric i.e., $w_{i\text{-}j} = 0.5$ for all i, j. Table 4 shows the computed quality metric values for each source node.

Source	**Quality Metrics values**			
	V_A	V_R	V_C	V_T
s_1	0.135251	0.087154	0.084104	0.036007
s_2	0.268516	0.17372	0.169778	0.074982
s_3	0.057909	0.073641	0.121676	0.137408
s_4	0.07114	0.109555	0.098994	0.137408
s_5	0.07272	0.05124	0.136487	0.115007
s_6	0.11825	0.031809	0.182018	0.095577
s_7	0.032877	0.109711	0.034218	0.111052
s_8	0.132956	0.275465	0.034218	0.176727
s_9	0.03801	0.037665	0.074677	0.074332
s_{10}	0.03801	0.018235	0.040528	0.020752
s_{11}	0.034363	0.031809	0.023306	0.020752

Table 4: Quality metrics values.

3.4. QoI-AHP based Quality of Information Score

To determine the candidate sources, the single aggregated QoI-score and priority of each source (shown in Table 5) is computed as the weighted sum of its respective quality metrics as in Equation (5). In the example, we assume the quality metric weights as in Equation (6), where W_i indicates the importance of a quality attribute i towards the overall QoI score and refers to the priority of the information need of the user. The weights are used for illustrative purposes considering a hypothetical application scenario. In practice, these weights are set according to the application quality metric preferences. In the example network, user node U chooses s_2 as the information source as it has the highest QoI score.

$$QoI\text{-}score = (V_A * W_A) + (V_R * W_R) + (V_C * W_C) + (V_T * W_T) \quad (5)$$

$$[W_A, W_R, W_C, W_T] = [0.4, 0.3, 0.2, 0.1] \quad (6)$$

Source	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
QoI-score	0.1006	0.2009	0.0833	0.0948	0.0832	0.1028	0.0640	0.1603	0.0488	0.0308	0.0300
Priority	4	1	6	5	7	3	8	2	9	10	11

Table 5: Source QoI score and selection order based on QoI-AHP method.

3.5. Problem Statement

The source QoI-score for the example network (in Table 5) depicts s_2 as the preferred choice of QoI-AHP due to its highest QoI-score; however, s_2 fails

to provide the required bandwidth ($t_{BW} = 0.3\,\text{Mpbs}$) for the user task and implies a negative impact on the timeliness and completeness of the queried information. Even if high weights are assigned to V_T and V_C and low weights to V_A and V_R, the timeliness and completeness requirements would still be not fulfilled by s_2 since the bandwidth value v_{BW} on the src-dst path from s_2 fails to meet the user expectation t_{BW} at the network layer. Furthermore, a source other than s_2 might be selected, which would have any other v_j (that contributes to V_A and V_R) still failing the corresponding t_j at the network layer. On the contrary, s_3 meets all needs (mentioned in subsection 3.1) but is ignored by QoI-AHP due to its comparatively low v_{IU} and v_{PI} values and is placed 6^{th} on the preference list. All its preceding source nodes fail to meet at least one network metric threshold. Since both p_{IU} and p_{PI} contribute towards V_A, which has the highest weight $W_A = 0.4$, the source nodes with higher relative values for v_{IU} and v_{PI} precede in overall QoI-score.

The sub-optimal source selection by QoI-AHP is caused by ignoring the fact that users vary in their requirements of a quality level. For example, a source node with *accurate* escape route information within a limited radius can be a better source for a user needing safe evacuation from that area. However, QoI-AHP may end up selecting an inappropriate source that shares a map depicting *complete* information about probable escape paths and shelter locations within a large geographical extent but may lack the up-to-date status of close-by paths. Such use cases necessitate specifying acceptable thresholds for different performance features of the desired information.

Furthermore, in a stressed network, the decision should not be based on a single QoI score but on the detailed capabilities of each source node. In the above example, another user at node 2 (for example) would also choose s_2 as its source as it also has the highest QoI-score for node 2. Relying on a single overall QoI-score could therefore lead the nodes to create bottlenecks that would further deteriorate the performance of the whole network. As mentioned earlier, another serious problem with QoI-AHP is the intensive computation process of AHP, where a user node performs a quadratic number of pair-wise comparisons for each source selection round.

Can we do better? We hypothesize that exploiting the fine-grained details about how well a source node can serve different quality requirements (of user application) will highlight the source nodes otherwise ignored by QoI-AHP, thus optimizing source assignment. In particular, we aim to find a solution with the following desired properties:

- **(P1)** Assigns for each user a source node that can best serve its needs

i.e., a source that satisfies as many threshold requirements as possible;

- **(P2)** Avoids overloading source node with traffic to multiple querying nodes by expanding the list of probable candidate sources; and
- **(P3)** Increases the number of users whose requirements are being met without incurring heavy computational overhead.

4. Requirement-based Source Selection Process

In this section, we propose a solution to deliver the properties **P1-P3** identified in the previous section. The objective is to improve the source selection process by using the fine-grained details regarding the ability of each source to meet user requirements. The key innovations in our approach compared to QoI-AHP are:

- we assign quality metrics priorities based on their importance to user;
- for each network metric, we define a threshold that depicts the required level of performance for user satisfaction, where user satisfaction indicates the fulfillment of an application's quality layer information needs;
- when available sources partially meet the quality needs of a user, we use the total number of quality metrics satisfied and the aggregate priority of quality needs successfully met by a source in selection process; and
- when all the required resources fail to meet, we use the extent to which each quality requirement fulfills in source selection.

We refer to our proposed source selection scheme as *QoI with thresholds (QoIT)*. QoIT is composed of source scoring and source selection mechanisms. QoIT scoring mechanism for a source is illustrated via a flow diagram in Figure 2. Assuming that the network metrics values along a *src-dst* path are already known, the technical details of Figure 2 for the example network are described below.

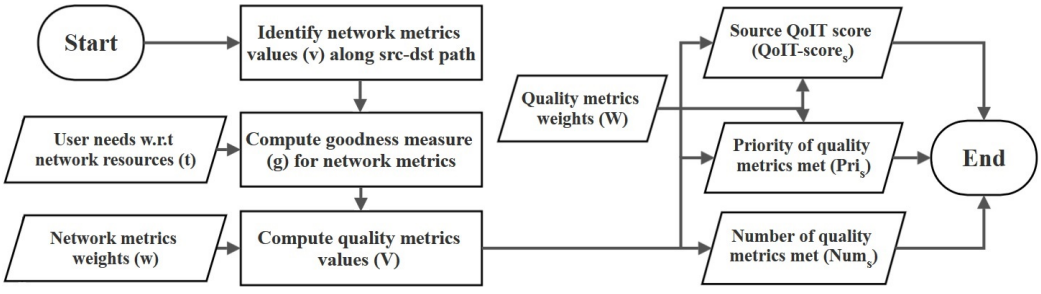


Figure 2: QoIT scoring procedure for a source s.

4.1. QoIT based Goodness Measure of Network Metrics Values

The first step in QoIT is to compute the goodness measure g for each network metric j, where g indicates how far a network metric value is from meeting the user demand. The value g of each network metric is the ratio of the available value v of a metric along the source to sink path (refer to Table 2) and the user requirement t regarding the network resource (refer to subsection 3.1). For hops count, the goodness value g_{HC} is evaluated as in Equation (7).

$$g_j = \begin{cases} 1.0 & \text{, if } v_j \leq t_j \\ t_j/v_j & \text{, otherwise} \end{cases} \tag{7}$$

For other metrics $j \in [BW, IU, PI]$, g_j is evaluated as in Equation (8).

$$g_j = \begin{cases} 1.0 & \text{, if } v_j \geq t_j \\ v_j/t_j & \text{, otherwise} \end{cases} \tag{8}$$

For the network metrics values in Table 2, the goodness measures are shown in Table 6. The g measure helps QoIT to achieve the threshold requirements (P1). Moreover, by excluding the QoI-AHP's pre-processing steps (applied to network metrics), QoIT incurs a low computational cost (P3).

Source	**Bandwidth**		**Hop Count**		**Info. Utility**		**Path Integrity**	
	Condition Met	g_{BW}	**Condition Met**	g_{HC}	**Condition Met**	g_{IU}	**Condition Met**	g_{PI}
s_1	$v_{BW} < t_{BW}$	0.33	$v_{HC} > t_{HC}$	0.75	$v_{IU} > t_{IU}$	1.0	$v_{PI} > t_{PI}$	1.0
s_2	$v_{BW} < t_{BW}$	0.66	$v_{HC} = t_{HC}$	1.0	$v_{IU} > t_{IU}$	1.0	$v_{PI} > t_{PI}$	1.0
s_3	$v_{BW} = t_{BW}$	1.0	$v_{HC} = t_{HC}$	1.0	$v_{IU} > t_{IU}$	1.0	$v_{PI} = t_{PI}$	1.0
s_4	$v_{BW} = t_{BW}$	1.0	$v_{HC} = t_{HC}$	1.0	$v_{IU} < t_{IU}$	0.6	$v_{PI} > t_{PI}$	1.0
s_5	$v_{BW} = t_{BW}$	1.0	$v_{HC} > t_{HC}$	0.75	$v_{IU} > t_{IU}$	1.0	$v_{PI} = t_{PI}$	1.0
s_6	$v_{BW} = t_{BW}$	1.0	$v_{HC} > t_{HC}$	0.5	$v_{IU} > t_{IU}$	1.0	$v_{PI} = t_{PI}$	1.0
s_7	$v_{BW} < t_{BW}$	0.66	$v_{HC} < t_{HC}$	1.0	$v_{IU} < t_{IU}$	0.4	$v_{PI} = t_{PI}$	1.0
s_8	$v_{BW} < t_{BW}$	0.66	$v_{HC} < t_{HC}$	1.0	$v_{IU} < t_{IU}$	0.4	$v_{PI} > t_{PI}$	1.0
s_9	$v_{BW} < t_{BW}$	0.83	$v_{HC} > t_{HC}$	0.75	$v_{IU} < t_{IU}$	0.98	$v_{PI} < t_{PI}$	0.5
s_{10}	$v_{BW} < t_{BW}$	0.5	$v_{HC} > t_{HC}$	0.5	$v_{IU} = t_{IU}$	1.0	$v_{PI} < t_{PI}$	0.5
s_{11}	$v_{BW} < t_{BW}$	0.5	$v_{HC} > t_{HC}$	0.5	$v_{IU} < t_{IU}$	0.5	$v_{PI} = t_{PI}$	1.0

Table 6: Goodness measure values for the network metrics in the example network.

4.2. QoIT based Quality Metrics Values

The second step in QoIT is to compute the value V_i of each quality metric i by taking the sum of the weighted goodness measures of the impacting network metrics, as shown in Equation (9). Note that $0 \leq V_i \leq 1$, where V_i indicates the extent to which a quality metric i is satisfied. $V_i = 0$ means the requirement does not meet at all, while $V_i = 1$ implies the requirement meets completely. For the goodness measures g of network metrics in Table 6, the V_i values are shown in Table 7. For a fair comparison, we take the same

weights of the network metrics as in QoI-AHP i.e., $w_{i\text{-}j} = 0.5$. However, in real-world problems, $w_{i\text{-}j}$ may vary with user needs.

$$\begin{aligned} V_A &= g_{PI} * w_{A\text{-}PI} + g_{IU} * w_{A\text{-}IU} \\ V_R &= g_{PI} * w_{R\text{-}PI} + g_{HC} * w_{R\text{-}HC} \\ V_C &= g_{BW} * w_{C\text{-}BW} + g_{IU} * w_{C\text{-}IU} \\ V_T &= g_{BW} * w_{T\text{-}BW} + g_{HC} * w_{T\text{-}HC} \end{aligned} \tag{9}$$

Quality metrics	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
V_A	1	1	1	0.8	1	1	0.7	0.7	0.74	0.75	0.75
V_R	0.875	1	1	1	0.875	0.75	1	1	0.625	0.5	0.75
V_C	0.6665	0.833	1	0.8	1	1	0.533	0.533	0.9065	0.75	0.5
V_T	0.5415	0.833	1	1	0.875	0.75	0.833	0.833	0.7915	0.5	0.5

Table 7: Quality metrics values w.r.t QoIT.

4.3. QoIT based Source Scoring Attributes

The next step is to assess the extent to which each source node can contribute to the required user requirements. For this purpose, QoIT computes:

- the number of quality requirements that each source node can fulfill;
- the priority level of quality requirements that each source node can meet; and
- how well each source node can satisfy the overall requirements.

To calculate the number of fully reachable quality metrics Num_s by a source s, we count the number of quality metrics with $V_i = 1$ as in Equation (10), where N is the total number of quality metrics and $I_{V_i=1}$ is the indicator function. $I_{V_i=1} = 1$ if $V_i = 1$ and 0 otherwise.

$$Num_s = \sum_{i=1}^{N} I_{V_i=1} \tag{10}$$

To compute the extent to which a source meets prioritized quality features Pri_s, we add-up the associated weights W_i (representing priority) of the quality metrics whose $V_i = 1$ as in Equation (11).

$$Pri_s = \sum_{i=1}^{N} W_{i|V_i=1} \tag{11}$$

Recall that W_i indicates the importance of a quality attribute i towards the overall QoI score and refers to the priority of the user's information need. In our example, W_is are given in Equation (6). The parameter Pri_s ranks a source s in terms of its capability to meet high priority requirements. The weights help QoIT to select a source that meets the requirements with the

highest aggregated priority, which is a significant improvement over QoI-AHP. For example, in situations where none of the sources completely meet all the quality requirements, QoIT prefers the source that has the ability to provide the essential quality features; which QoI-AHP may not as it chooses the source with the highest overall QoI score (irrespective of the aggregated priority score of the quality metrics it meets). If multiple sources have the same Pri value, then the parameter Num assists in identifying the source that meets higher priority requirements.

If none of the sources meet any quality needs, then a third score *QoIT-score* is used, which evaluates as the linear sum of the product of each V_i with its weight W_i as in Equation (12). *QoIT-score* assesses the weighted extent to which each quality need fulfills. In-fact the QoIT-score of 1 (calculated based on the achieved priority scores of the quality metrics met) indicates that the source meets all the quality requirements. QoI-AHP often assigns a lower QoI score (due to the pre-processing steps of AHP) to a source that meets all the quality requirements and selects the highest QoI scoring source that fails certain quality needs. In such a situation, QoIT considers the QoIT-score of all sources and selects the one with a QoIT-score of 1. The results of all these assessment factors for the example network are shown in Table 8.

$$QoIT\text{-}score_s = (V_A * W_A) + (V_R * W_R) + (V_C * W_C) + (V_T * W_T) \quad (12)$$

Source	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
QoIT-score	0.849	0.949	1.0	0.880	0.950	0.900	0.769	0.769	0.743	0.650	0.675
Pri	0.4	0.7	1.0	0.4	0.6	0.6	0.3	0.3	0.0	0.0	0.0
Num	1	2	4	2	2	2	1	1	0	0	0

Table 8: QoIT-based source assessment w.r.t the extent to which user needs are met.

4.4. QoIT based Source Selection Criteria

Figure 3 illustrates the source selection criteria of QoIT via a flow diagram, where the selection hierarchy considers $QoIT\text{-}score_s$, Num_s, and Pri_s of each source s as an input. The selection hierarchy ends-up selecting a source s that satisfies one of the selection criteria, where each criterion is applied sequentially in order of its preference. Multiple selection criteria aim at delivering property P2 and P3. Below, we discuss the technical details of these criteria in order of their preference.

Criterion 1: Source QoIT-score $s_c = 1$ implies that the source can meet all the quality needs of an application. In the case of a single source with $s_c = 1$, the selection is trivial; however, when multiple sources meet all the quality needs, the selection is random among the candidate nodes as in Equation (13). Though preference can be given to the source that maximizes the

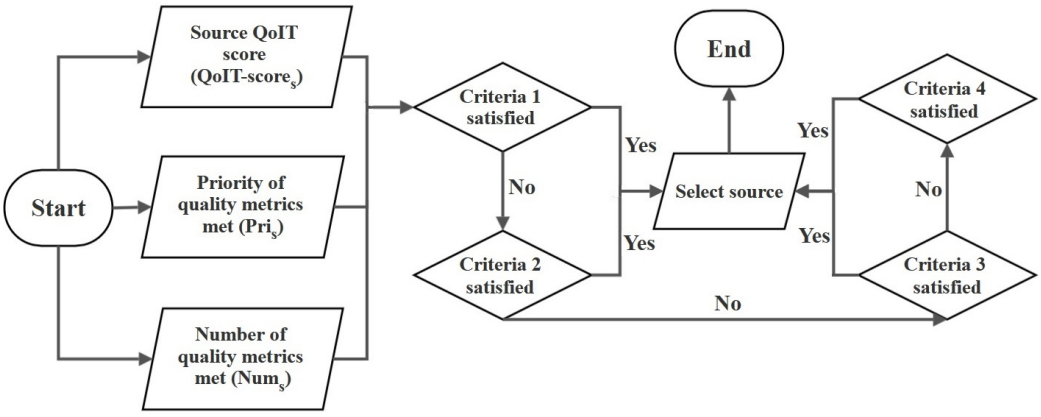


Figure 3: Source selection process in QoIT method.

important requirements, it may overload the source and will generate a bottleneck on the links from the source when assigned to multiple querying nodes. Random selection helps in balancing the load among sources.

$$src = \begin{cases} s_c & \text{, where } QoIT\text{-}score_c = 1 \text{ and } |s_c| = 1 \\ any(s_c) & \text{, } \forall\ QoIT\text{-}score_c = 1 \text{ and } |s_c| > 1 \end{cases} \tag{13}$$

Criterion 2: Situations where none of the sources completely meet all quality needs, QoIT considers candidate source node s_c that has the maximum priority score Pri_c regarding the quality metric(s) it fully meets. In the case of multiple sources with the same Pri_c, QoIT selects the source that meets the minimum number of quality metrics Num_c. It is to ensure that the chosen source satisfies the high priority quality metric(s). Selection under this criterion is given in Equation (14).

$$src = \begin{cases} s_c, \text{ where } max(Pri) = Pri_c \text{ and } |s_c| = 1 \\ s_{ci}, \text{ where } max(Pri) = Pri_c,\ min(Num_c) = Num_{ci} \text{ and } |s_c| > 1 \end{cases} \tag{14}$$

Criterion 3: In the case of a tie among multiple sources regarding criterion 2, preference is given to the source with the maximum QoIT-score. However, if a tie on QoIT-score also exists, it is broken by random selection as in Equation (15).

$$src = \begin{cases} s_{cij}, \text{ where } max(QoIT\text{-}score_{ci}) = QoIT\text{-}score_{cij} \text{ and } |s_{cij}| = 1 \\ any(s_{cij}), \text{ where } max(QoIT\text{-}score_{ci}) = QoIT\text{-}score_{cij} \text{ and } |s_{cij}| > 1 \end{cases} \tag{15}$$

Criterion 4: If none of the sources meet any quality threshold i.e., $Num = 0$ and $Pri = 0$, then QoIT-score acts as the deciding factor as in Equation (16).

$$src = \begin{cases} s_c, \text{ where } \mathit{QoIT\text{-}score}_c = max(\mathit{QoIT\text{-}score}) \text{ and } |s_c| = 1 \\ any(s_c), \text{ where } \mathit{QoIT\text{-}score}_c = max(\mathit{QoIT\text{-}score}) \text{ and } |s_c| > 1 \end{cases} \quad (16)$$

To evaluate the working of both schemes, we assess the preference order of sources in the example network (Figure 1). For ranking, QoIT applies *Criterion 1-4* on the decision attributes listed in Table 8, whereas QoI-AHP uses the decision parameters mentioned in Table 5. Table 9 shows the ranking of source nodes for both schemes and highlights the criteria that QoIT applies for each source node. We now determine the capabilities of the source nodes, in terms of their ranking by both methods, as follows:

(1) Among *all* source nodes, s_3 is the only source with a QoIT score of 1, which means that it can meet all the quality expectations of a user and is best among all source nodes. On the other hand, QoI-AHP chooses s_2 (due to its highest QoI-score) that meets only half of the quality needs i.e., $Num = 2$. QoIT out-performs QoI-AHP in satisfying user needs.

(2) As a *second* preference, QoIT chooses s_2 that meets two higher priority metrics, while QoI-AHP chooses s_8 (2^{nd} in its priority list) that fulfills only a single metric. Again, QoIT leads in performance.

(3) As a *third* preference, QoIT selects s_5, whereas QoI-AHP chooses s_6. Both the sources meet the quality metrics of the same priority with $Pri = 0.6$ and $Num = 2$. But the higher overall *QoIT-score* of s_5 indicates its closeness in satisfying the overall quality features. QoIT again proves to be a better choice.

(4) As *fourth* preferred source, QoIT selects s_6 having $Pri = 0.6$ and $Num = 2$, whereas QoI-AHP chooses s_1 having $Pri = 0.4$ and $Num = 1$. Both this and the earlier use-cases verify better decision making power of QoIT.

(5) The *fifth* preferred source, for QoIT is s_1 with $Pri = 0.4$ and $Num = 1$, while for QoI-AHP is s_4 with $Pri = 0.4$ and $Num = 2$. The selection of QoIT is considered better since s_1 meets the high priority quality metric i.e., *accuracy*.

(6) The *sixth* ranked source by QoIT is s_4 that meets only two metrics. Though this time, QoI-AHP chooses s_3 that fulfills all the metrics, its low ranking reveals the weak decision power of QoI-AHP.

(7) The *seventh* ranked source of QoIT is s_7, and for QoI-AHP is s_5. Source s_5 meets more metrics than s_7 and is already ranked higher by QoIT.

(8) The *eighth* preferred source of QoIT is s_8, and for QoI-AHP is s_7. Both the sources meet a single and same priority quality metric (indicated by their Pri and Num values) and have the same capability in the provision of different quality requirements (indicated by their QoIT-score).

(9) The *ninth* preferred source node is the same for both the schemes i.e., s_9.

(10) The *tenth* ranked source of QoIT is s_{11}, and for QoI-AHP is s_{10}. s_{11} is a better choice due to its higher QoIT-score, indicating its closeness in providing the

required features.
(11) The *least* preferred source by QoIT is s_{10}, and by QoI-AHP is s_{11}. Once again, the ranking of QoIT is better as s_{10} has the lowest QoIT-score and is farthest in meeting requirements.

Source	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
Criterion Used	2^{nd}	2^{nd}	1^{st}	2^{nd}	3^{rd}	2^{nd}	3^{rd}	3^{rd}	4^{th}	4^{th}	4^{th}
QoIT	5^{th}	2^{nd}	1^{st}	6^{th}	3^{rd}	4^{th}	7^{th}	8^{th}	9^{th}	11^{th}	10^{th}
QoI-AHP	4^{th}	1^{st}	6^{th}	5^{th}	7^{th}	3^{rd}	8^{th}	2^{nd}	9^{th}	10^{th}	11^{th}

Table 9: Selection preference of source nodes w.r.t both schemes.

5. Evaluation

5.1. Simulation Model and Experimental Setup

To evaluate QoIT and QoI-AHP, it is important to have a simulation tool that has built-in support for network metrics such as information utility and integrity. These metrics are crucial for calculating the instantaneous information quality metrics required in QoIT and QoI-AHP. Even though tools such as NS3 and Omnet++ provide realistic models of the physical, MAC, and routing layers, they do not support information quality based measures. Information accuracy, for example, requires knowledge of the security mechanisms deployed on each link. For this purpose, we extend the simulation environment built with JAVA APIs in [12] that has native support for these information metrics. We implement the QoIT source selection process by polling in real-time the required network metrics from the simulator. Below we discuss some of the features of this software used at different layers of the simulated network. In future work, we will investigate methods to incorporate our QoIT and QoI-AHP implementation as a plug-in into simulation tools such as NS3.

5.1.1. Physical Layer

Our simulated network uses the standard log-distance path loss model under dense foliage to calculate the radio attenuation and data rate at the physical layer. Complex models can be used if different attenuation effects are deemed necessary e.g., by adding noise or terrain effects. Network connectivity on a link between two nodes exists if its capacity is greater than 0 Mbps. SNR generated using Equation (17) is used to calculate the data rate of a link according to Shannon's capacity. We assume all radios to be transmitting on the same frequency band such that interference occurs if nodes within the range are transmitting simultaneously.

$$SNR = T_p - 32.45 - 4 * 10log10(f * d) - r - n_{cutoff} \tag{17}$$

where T_p is the radio transmission power with simulation using 20 dBm value, f is the carrier frequency within 2.4 GHz band, d represents Euclidean distance between two end nodes in km, r represents random fading ranging from 0-1 dB, and n_{cutoff} is the Nyquist noise cutoff level with -180 dBm.

Our simulation field is a 20 km^2 area. Each test scenario has a 36-node network, where 6 nodes serve as static source nodes and the remaining 30 nodes are querying nodes. Each node could act as a relay for others. Test scenarios are divided into two categories based on the mobility features of 30 querying nodes; they all are either (1) static or (2) mobile. In mobility scenarios, the nodes can be of four types, those with owners walking, running, cycling, and driving cars. We assume average speed ranges in each case as is mentioned in [47, 48], where for walking the range is 0-5 km/hr, for running 7.5-13.5 km/hr, for cycling 16-24 km/hr, and for cars 50-90 km/hr (considering the average speed in residential areas and on main roads). We run each scenario twenty times, wherein each run, the nodes have different starting positions. Furthermore, in mobility scenarios, the position of querying and relay nodes are updated 30 times per run, whereas a run completes in 20-35 sec. The direction of movement path is initially chosen at random for each node, which is retained for later movements to imitate the movements of real-world objects.

5.1.2. Data Link Layer

For medium access sharing and control, we use the Time Division Multiple Access (TDMA) protocol as it is the most widely used MAC protocol in current MANETs [49]. In particular, we used the Node Activation Multiple Access (NAMA) [50] based slot reservation scheme for bandwidth allocation, where the resource reservation is accomplished immediately after source selection. The contention resolution approach of NAMA enables collision-free scheduling by using two-hop neighborhood information to dynamically determine, at each node, if it can transmit in a time slot. NAMA's distributed scheduling uses hash functions to generate a pseudo-random number for each node and determine the priority among contending two-hop neighbors. NAMA generally leads to a fairer allocation of resources, especially in congested networks. This is an important consideration in an emergency scenario where data must be received by each user. Determining the best possible version of the scheduling protocol for this network is an interesting question, but is beyond the scope of the current work.

5.1.3. Network Layer

To establish the shortest routes between end nodes, we implement Dijkstra's shortest path algorithm. The established paths are used both to route users and control traffic. The weight of a path between two end nodes is equal to the sum of the weights on its links, where the weight of a link is equal to the inverse of the data rate on the link. The shortest path is the one with the smallest sum of weights of its links. In the mobile scenario, the distance and random fading between nodes are evaluated in order to decide the link set-up/breakage and its data rate. In the simulations in this paper, unless otherwise stated, we use the same weight for each pair of network metric j towards its corresponding quality

metric i, i.e., $w_{i\text{-}j} = 0.5$ for all i, j, assuming that all network metrics are equally important for the application layer attributes.

5.1.4. Application Layer

In the test network, all traffic goes from source nodes towards querying nodes. Since our goal is to provide users with what they need, we do not model any specific application data type. We rather synthesize differences in desired features of queried data by defining minimum requirements of network metrics. Querying nodes query available sources simultaneously to select a single source for information retrieval. It is assumed that all the source nodes possess similar information but with varying performance features. In our simulations, to indicate the importance of the quality attributes towards an overall quality score, a hypothetical application scenario is assumed where the quality metric weights are assigned as in Equation (6). The weights can be adjusted in accordance with user needs.

5.2. Results and Analysis

We evaluate the performance of the proposed QoIT and the QoI-AHP source selection methods under three different scenarios. The scenarios are illustrated in Table 10, which includes varying the number of querying nodes, the mobility speeds, and the user requirements. To evaluate the performance of the schemes, we use the parameters listed in Table 11.

Scenarios	**No. of Querying Nodes**	**Description**
Varying number of user nodes	3, 6, 12, 18, 24, 30	Static nodes
Same vs different requirements	30	Static nodes
Different mobility speeds	30	Human walking and running speeds, cycling and car speeds

Table 10: Test scenarios.

	Performance Parameter	**Description**
1.	*Average overall priority of the requirements met*	It indicates the mean of the cumulative achieved priorities for all users in a run. For a single user, Equation (11) computes the cumulative priority, Pri_s of the completely met quality features by the selected source s.
2.	*User usability*	It indicates the percentage of querying nodes meeting all quality metrics.
3.	*Computational time*	It represents the time taken by each scheme in assigning a source node to a querying node.
4.	*Load at source*	It shows how frequently a particular source is selected by querying nodes.
5.	*Scalability and robustness*	To understand the impact of user usability in terms of varying querying nodes, mobility speeds and user requirements.

Table 11: Performance parameters.

5.2.1. Average Overall Priority of the Requirements Met

We start by looking into the AHP-scores of the selected source nodes by the two methods. In Figure 4a, the left-skewed density function of the AHP-scores of the

sources selected by QoIT reveals that for a significant number of times, the QoIT method prefers the source nodes that are considered less capable by QoI-AHP. The high AHP scores of QoI-AHP, however, do not ensure good performance when minimum requirements are defined. Figure 4b shows that the low AHP-scoring sources chosen by QoIT improve the median priority of the quality metrics met by almost 40% to that of QoI-AHP.

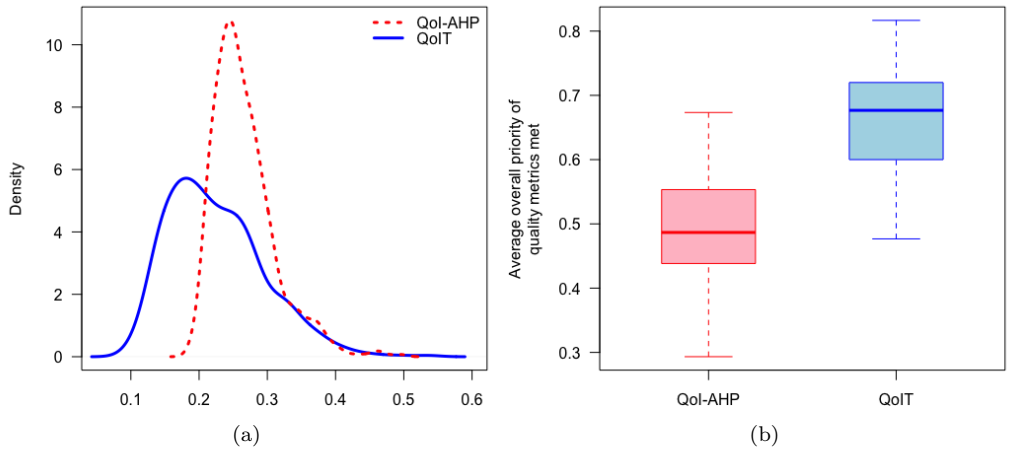


Figure 4: Performance of both schemes w.r.t (a) AHP score of the selected nodes and (b) average overall priority value of fulfilled requirements (static 30 querying nodes scenario).

5.2.2. User Usability

Taking the recent bushfire in Australia as a case study, in similar catastrophic scenarios, the residents at vulnerable places need timely information regarding available emergency services, the exact and close-by safe public places, reliable information regarding food and water supply at sheltered areas, and accurate updates regarding the situation in their surrounding areas. This implies rescue and surveillance networks to outsource all needed details in the desired manner to the maximum number of vulnerable people i.e., to maximize the user usability (percentage of users whose all quality metrics requirement meet).

To analyze user usability of both selection schemes within an ad hoc network, we take a static scenario with 30 querying nodes. The stacked bar chart of Figure 5a shows the percentage of querying nodes with different number of quality metrics being fulfilled. For QoIT, we observe an increase of almost 57% in the number of querying nodes whose all four requirements are fulfilled, as compared to QoI-AHP. Even the case of two fulfilled requirements shows that QoIT directs 3% more querying nodes to comparatively better source nodes. Note that no user node meets three quality requirements, the reason being each network metric in our experimental setup contributing to two quality metrics. If a single network

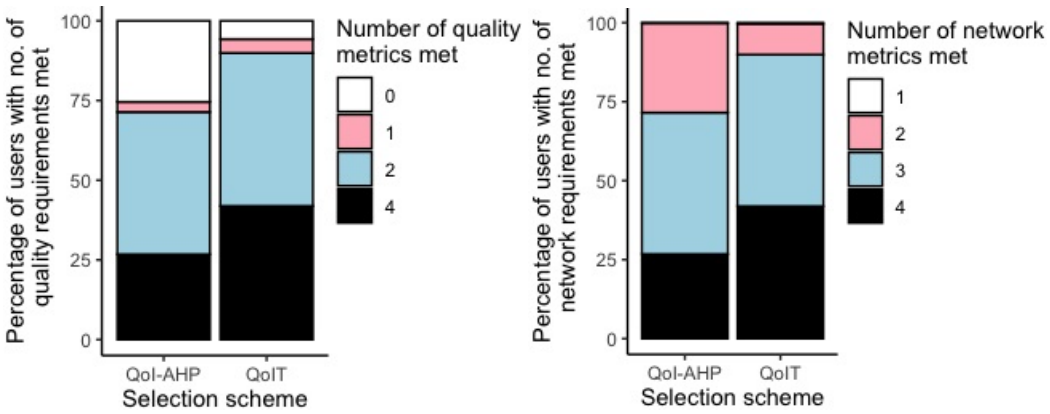


Figure 5: Percentages of users with different number of requirements fulfilled at (a) application and (b) network layer (static 30 nodes scenario).

requirement remains unfulfilled, it impacts two quality metrics. This has been verified by Figure 5b, which shows multiple querying nodes in both the QoIT and QoI-AHP, with only three network metrics met. The test proves that in an emergency ad hoc network, the needed information can be outsourced in the desired way to a larger number of people, with the QoIT method.

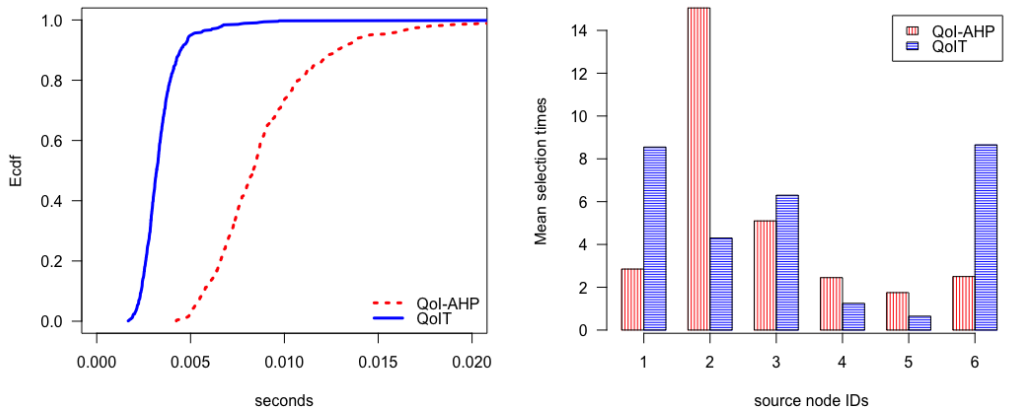
5.2.3. Computational Time

Besides improving service provision to querying nodes, QoIT also incurs less computational time than the baseline method of QoI-AHP. Figure 6a displays the empirical distribution function (ecdf) of the time taken by each method in assigning a source node to a querying node. Experiments are run on a commercial off-the-shelf system with an Intel(R) Core i7 processor (2.6GHz). Both schemes assume that the network characteristics on the links towards each source node are already known. The figure shows decision computation time for all 20 runs of 30 static querying nodes scenario. With QoI-AHP, computational time seems to start from 4 ms that goes up to 0.05 seconds; while in QoIT, above 90% of the assignments are performed under 4 ms. The reason for less computational time consumed by QoIT is its exclusion of the lengthy pre-processing steps of QoI-AHP. The small computational cost adds to QoIT, especially when early warnings regarding unexpected emergency in otherwise low-risk areas can save lives.

5.2.4. Load at Source

Figure 6b shows the average load on the source nodes i.e., the average number of times a source is assigned to querying nodes, in the static 30 querying nodes scenario. In our experiment, source 2 has the highest *information utility* score that contributes to the highest weighted quality metric of *accuracy*. The single score se-

lection process of QoI-AHP ends-up assigning source 2 to multiple querying nodes. As expected, consideration of requirement thresholds by QoIT increases the number of candidate source nodes, which lowers the load on few "best-known source node(s)" of QoI-AHP. The same is obvious in Figure 6b, where QoIT distributes the load comparatively evenly on the candidate source nodes $1, 2, 3$, and 6.



(a) (b)

Figure 6: Distribution of (a) computation time taken by both schemes in assigning a source node to a querying node and (b) mean number of times a source node is assigned to querying nodes w.r.t both schemes (static 30 querying nodes scenario).

5.2.5. Scalability and Robustness

To assess the scalability and resilience of QoIT against QoI-AHP, we evaluate their performance both under the increasing number of querying nodes and varying mobility speeds. For scenarios where querying nodes are less (e.g., 3 in Figure 7a) than the source nodes (which are 6), the overall user usability is lower than expected for QoI-AHP. This is in-line with what we observed earlier with the example network in Table 9, where QoI-AHP has to assign a source among eleven sources to a single querying node. There we found that the source which had the ability to meet all the quality metrics was placed sixth in the preference list by QoI-AHP and was not considered for selection. It indicates the under-utilization of resources by QoI-AHP. We see no such limitation with QoIT as it scales as expected. For the querying nodes, equal to or greater in number than the source nodes, the user usability of both the schemes gradually drops with the increasing number of querying nodes, as shown in Figure 7a. The obvious reason is the increase in the supply and demand gap. Also, with an increase in mobility speed, the number of querying nodes going out of the range of source nodes increases with each movement step (i.e., 30 steps in each run). Therefore, we see a clear drop in the percentage of querying nodes with all requirements met, especially in the car driving scenario

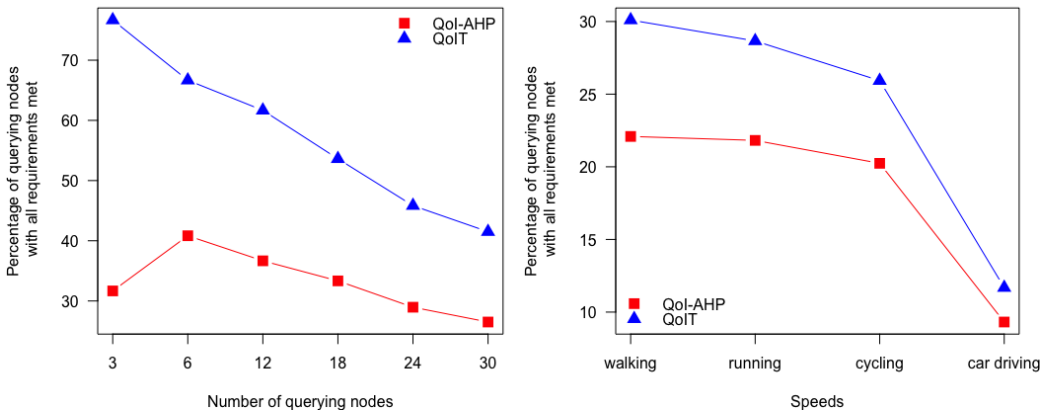


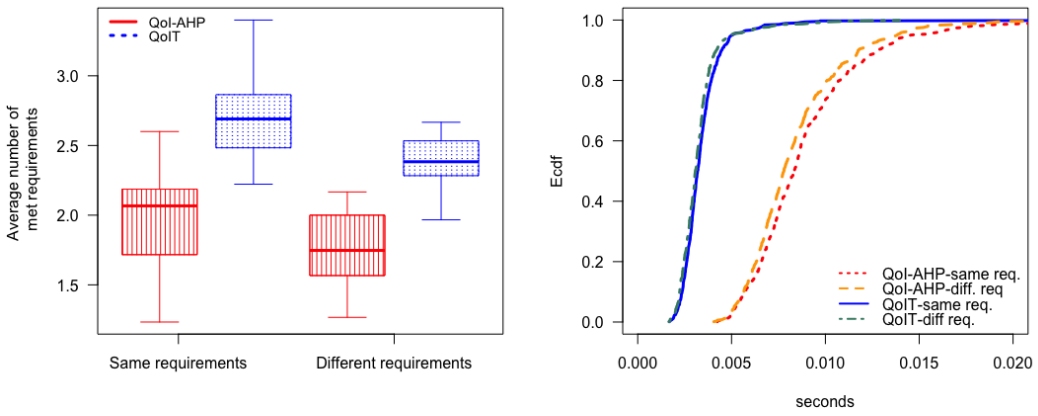
Figure 7: Percentage of querying nodes meeting all needs w.r.t (a) different number of querying nodes (static scenario) and (b) different speed ranges (mobile 30 nodes scenario).

shown in Figure 7b. In short, Figure 7a and Figure 7b demonstrate that with the increasing contention and decreasing number of candidate source nodes, respectively, both the methods face a slightly steeper drop in the performance, but with QoIT retaining relatively higher user usability in all the cases.

Lastly, we investigate and analyze the capability of QoIT in assigning better sources when the requirements of the querying nodes vary. In the case of *similar* requirements, we take the same network metrics thresholds for all querying nodes. In contrast, in *different* requirements case, the threshold values are randomly chosen for each querying node within the ranges given in Table 12. Here the threshold selection from the large ranges of both hop count and information utility imposes higher constraints by the querying nodes than in the case of *similar* requirements. This is obvious from Figure 8a, with a lower average number of quality metrics met for the querying nodes when they have *different* needs. An interesting finding is that with the difference in requirements, the variability of both the schemes decreases. With QoIT, the median drop in performance is 11, which is better than the drop of QoI-AHP i.e., 15%. This indicates that QoIT is relatively robust when users are interested in different types of services, and with no additional time consumption as indicated by Figure 8b.

Network Metrics	**Similar Requirements**	**Different Requirements**
Bandwidth	0.3 Mbps	0.001 Mbps to 0.3 Mbps
Hop Count	8	1 to 10
Path Integrity	2	1 to 4 units
Information Utility	5	3 to 10 units

Table 12: Network metrics thresholds.



(a) (b)

Figure 8: Distribution of (a) average number of requirements met by both schemes and (b) time complexity of both schemes, when requirements of all querying nodes are similar and different (static 30 querying nodes scenario).

As a takeaway, compared to QoI-AHP, QoIT increases the user usability by 57% and takes 62.5% less time in source selection and assignment to a querying node. QoIT not only decreases the load on source nodes by increasing the number of candidate source nodes but also outperforms QoI-AHP in various scenarios. The scenarios comprise of querying nodes being less or more than the source nodes, with varying mobility speeds of the querying nodes and with both the same and different requirements of the querying nodes.

6. Limitations and Discussions

In QoIT, we have assumed that quality features required by an application are known and are already mapped into corresponding network features in the form of threshold values. Furthermore, for simplicity reasons, both schemes consider the same weights for different network features contributing to a quality feature. Though it is out of the scope of this paper, there are a number of research studies both regarding quality features required for an application as mentioned in Table 1 and mapping of network metrics to quality metrics and vice versa [51–53]. The studies have mostly used regression and classification methods to predict the value of a feature [54] from other known features. Additionally, querying nodes in both the schemes assume to have the knowledge of the network state and about the capabilities of the source nodes. Again being out of the scope of the paper, interested readers can read about distributed hash tables (DHT) [55] used to search for resources requested by peers or proactive and reactive methods [56] commonly used for announcing both routing paths and resources within a network. Moreover, in the study, we have taken a simple log-distance path loss formula for calculating

bandwidth along a link, which can be extended to more realistic empirical methods by incorporating weather conditions and intensity of multi-path fading depending upon the terrain under consideration.

7. Conclusion

In today's world, cellular networks are mature enough to meet the various requirements, such as high data rate, low latency, and high mobility. An alternative method for communication is however needed when both communication and power infrastructures are not available for some reason, such as failure of infrastructure and towers due to natural disasters, as in the case of recent bushfires in Australia. MANETs are an alternate method to connect people and to provide rescue and emergency services.

Due to unstable links and limited resources in MANET, it is desired to use ways that can optimize service provision. In this paper, we proposed an information source assignment method called QoIT. It exploits thresholds of network layer features such as required bandwidth, hops count, and path integrity to meet the application layer requirements such as desired timeliness and accuracy of the information, in choosing a source node. The inclusion of thresholds not only increases the candidate list of source nodes but also avoids getting information from less capable source nodes. Compared to the baseline method of QoI-AHP, QoIT increases user usability and reduces source selection time by more than half. It does not overburden the same set of sources by assigning it to multiple querying nodes; instead distributes the load more evenly. In addition to this, QoIT proves to retain its better performance compared to QoI-AHP under a varying number of querying nodes, varying mobility speeds, and varying quality requirements.

In the future, we aim to extend the QoIT scheme to a peer-to-peer network and to deploy primary source nodes in the form of Unmanned Air Vehicles (UAVs) in the bushfire scenario. If so, the questions to be addressed would be how many UAVs are needed for a network with a particular size and users' mobility speeds, and how to optimize the locations of these UAVs based on the network topology and traffic requirements.

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Appendix A. QoI-AHP related Pre-processing Steps

In the first step, each network metric value is scaled to the [0-1] range as shown in Table A.1, to make the corresponding metrics comparable with one another. The scaling is achieved by dividing a network metric value by the highest value offered by any source, with an exception for hop count where it is further subtracted from 1. For the example network, the highest values are $[h_{BW}, h_{HC}, h_{IU}, h_{PI}] = [0.3, 6, 10, 4]$ derived from Table 2, where h_j indicates the highest value for network metric j.

Source	v_{BW}/h_{BW}	1 -(v_{HC}/h_{HC})	v_{IU}/h_{IU}	v_{PI}/h_{PI}
s_1	0.33	0.33	0.75	0.75
s_2	0.66	0.5	0.97	1.0
		...		
s_{11}	0.5	0.0	0.25	0.5

Table A.1: Scaled ([0-1] range) network metric values.

Next the difference (Δv) of the corresponding scaled network metric values (from Table A.1) between different sources are calculated to determine the relative importance of every source with respect to each network metric. Table A.2 indicates these calculations for bandwidth (i.e., Δv_{BW}). Similar calculations can be done for $\Delta v_{HC}, \Delta v_{IU}$, and Δv_{PI}. This step includes expensive computation steps of $O(n^2/2)$.

Δv_{BW}	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
s_1	0.0	-0.33	-0.66	-0.66	-0.66	-0.66	-0.33	-0.33	-0.5	-0.16	-0.166
s_2	0.33	0.0	-0.33	-0.33	-0.33	-0.33	0.0	0.0	-0.16	0.16	0.16
					...						
s_{11}	0.16	-0.16	-0.5	-0.5	-0.5	-0.5	-0.16	-0.16	-0.33	0.0	0.0

Table A.2: Difference (Δv) of corresponding bandwidth ratio of different sources.

Thirdly according to the heuristics applied by Chan et al. [11], fixed scores are assigned to each relative difference Δv to build a pairwise comparison matrix. The corresponding comparison matrix for the bandwidth is shown in Table A.3 and similar matrices can be built for the rest of network metrics.

Bandwidth	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
s_1	1	0.2	0.14	0.14	0.14	0.14	0.2	0.2	0.14	0.33	0.33
s_2	5	1	0.2	0.2	0.2	0.2	1	1	0.33	3	3
					...						
s_{11}	3	0.33	0.14	0.14	0.14	0.14	0.33	0.33	0.2	1	1
Col. Sum	55	26.8	5.3	5.3	5.3	5.3	26.8	26.8	14.5	36.3	36.3

Table A.3: Comparison matrix for bandwidth.

The comparison matrix is then normalized as in Table A.4. Once the normalized comparison matrices are evaluated for each network metric, finally the alternative priority vector is generated for all the metrics.

BW	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
s_1	0.0181	0.0074	0.0266	0.0266	0.0266	0.0266	0.0074	0.0074	0.0098	0.0091	0.0091
s_2	0.0909	0.0372	0.0373	0.0373	0.0373	0.0373	0.0372	0.0372	0.0229	0.0825	0.0825
						...					
s_{11}	0.0545	0.0123	0.0266	0.0266	0.0266	0.0266	0.0123	0.0123	0.0137	0.0275	0.0275

Table A.4: Normalized comparison matrix for bandwidth.