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Soft-GORA: Soft Constrained Globally Optimal Resource Allocation for Critical Links in IoT Backhaul Communication

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ABSTRACT The Internet of Things gateways with multi-radio facilities in wireless networks can simultaneously communicate using multiple available channels. This feature enhances the carrying capacity of wireless links and thus increases the overall network throughput. However, designing an efficient resource allocation strategy is a complex task due to the decisive behavior of interference. There is only a limited number of available channels; therefore, the resource allocation requires careful planning to mitigate the effect of interference. This research proposes a backtracking search-based resource allocation scheme that maps resource allocation to the constraint satisfaction problem. Some of the resource allocation constraints are applied as soft constraints which are relaxed to find a feasible solution, provided the perfect allocation of limited resources is not possible. The proposed approach has been benchmarked through simulations and the results prove the effectiveness of the proposed approach especially in dense multi-hop network deployments.

INDEX TERMS Internet of Things, multi-hop networks, channel quality, channel utilization, globally optimal, constraint satisfaction problem, backtrack searching.

I. INTRODUCTION

The emergence of internet of things (IOT) is making routine objects the part of internet. A massive amount of data from these objects is generated and relayed towards the data centers for analysis. In some cases, this analysis may be of real time nature that requires instant actuation. At the access level, the objects may be forming network using different technologies and similarly, for backhaul communication a variety of networks are also available [1]. The deployment of multi-hop IoT networks is a reliable and cost-effective alternative that is used to provide a high data rate of backhaul services and therefore, it requires better performance parameters. The practical deployments of these networks are still far from reaching full realization and therefore, in recent years, it has drawn close attention from the research community and industry. The gateways (GWs) in IoT networks can have multiple radios [2]–[5] and thus interference estimation should be based on all radios, which does not usually pose a difficulty in traditional networks as routers are equipped with only a single radio. However, GWs equipped with multiple radios can also experience some complexities as parallel transmissions in close proximity cannot occur on the same channel at the same time. Assigning each radio, a different channel is practically not possible as this may result in logical disconnection of the network topology. Besides, the number of available channels is usually less than the number of radios in proximity. There are 3 and 12 non-overlapping channels in IEEE 802.11b and a, respectively [6]–[9].

The proposed resource allocation scheme facilitates broadening the access of high data rate network and internet services to isolated areas under IoT. Traditional resource allocation solutions provide different metrics such as channel ranking [10]–[12], cost [13] and weight [14], [15]. A better solution using the above-mentioned metrics has been selected as the new channel. However, due to the limited number of resources (channels), in scaled networks, each time it is not practical to assign a different or non-conflicting channel to the incident links.

This research maps the resource allocation problem to the Constraint Satisfaction Problem (CSP). In solving the classical CSPs, the goal in general is to find a feasible solution, such as allocating channels to the wireless links in such a way that every constraint is satisfied. However, the resultant feasible solution may not be optimal [16]. Therefore, to achieve both goals, the standard satisfaction framework is extended to include the definition of soft constraints. These soft constraints are relaxed to find a feasible solution, provided the perfect assignment of limited resources is not possible. For soft constraints, the proposed approach uses an ordered list of wireless links that need to be allocated with the new channels and the ordered list of the supported channels. Solving the constraint satisfaction problem (with an increase in the channels, size of network and flows) is also a challenging task. However, using simple search algorithms, it is hard to find such solutions. The best combinatorial-suited process is the exploitation of a backtracking search algorithm that helps to prune the non-promising solutions that do not need to be searched. Accordingly, an optimal or near-optimal solution can be found. The two-fold contribution of this work as follows:

- Allocation of a globally best available channel that is also consistent and soundest at the local level.
- Additionally, this approach does not lead to deadlocks where there are no channels available for the incident links. Previously, such deadlock situations were handled by assigning random channels, but this approach instead finds a definite solution using best available data structure.

The rest of the paper is organized as follows; Section 2 provides the literature review. The design of proposed scheme is discussed in Section 3. Section 4 explains the Soft-GORA model by presenting constraints modeling, example scenario of search tree and accordingly its algorithm. The experimental analysis and performance evaluation is presented in Section 5.

II. LITERATURE REVIEW

In wireless networks, the problem of resource allocation has been formulated as a graph-colouring problem in some of the schemes [17], [18], where the vertices of a graph are coloured subject to certain constraints. These constraints include, for example, no two adjacent vertices having the same colour. In vertex colouring solutions, the colouring is based on a chromatic number [19], that defines the minimum number of colours required to successfully paint the graph in a way that no two adjacent vertices have the same colour. The IEEE provides a limited number of available channels (such as three in 802.11b/g and twelve in 802.11a standard respectively) [20]. Therefore, due to the limited number of channels in 802.11, in scaled networks it is not possible to practically assign a different or non-conflicting channel to the adjacent links each time. In these situations, the ultimate option used in the literature is to assign a random or less conflicting channel to the incident link. The Carrier Sense Multiple Access (CSMA) protocol, by design, handles the contention of such channel assignments by distributing the airtime among the contenders [21]. Therefore, due to over-enforcement of resource allocation constraints, minimum number of channels (chromatic number), the classical vertex colouring solutions cannot be directly mapped to resource allocation problems [22].

Riggio *et al.* [23] have used a random channel, provided their proposed approach was unable to find any non-conflicting channel. Such random selection does not perform well, especially in heavy traffic load scenarios [24]. The practical deployments have also witnessed that such random selections become the reason for adjacent and Co-Channel Interference (CCI) [25]. Multiple researches have also articulated the fact that better approaches can be adopted rather than merely choosing a random channel [26]–[28].

Similarly, the resource allocation schemes [29] that formulate the problem of resource allocation as a Linear Programming (LP) problem, make use of objective functions. The focus of such objective functions is to optimize the cost of a solution so as to minimize interference, and maximize capacity or throughput. .Chieochan and Hossain [30] have formulated the resource allocation problem as a linear program that optimizes the throughputs of all links subject to the constraints of interference, coding and the number of available channels. Similarly, Chaudhry *et al.* [18] used the objective function to maximize the throughput while following the constraint of fairness. These schemes apparently resolve the issue by providing the best available option that also fulfills the constraints. Comparatively, if these solutions are analyzed in the local and global context, these solutions are only possible in the local sense.

The most that can be guaranteed by these minimization/maximization techniques is that it finds the local minimum/maximum. Lasdon [31] has stated in his book that every local minimum may not be a global minimum and every maximum may not be a global maximum. Furthermore, a study by Zhu and Wang [32] identified that the computation time of LP-based approaches is too high to be acceptable and therefore suggested that efficient heuristic methods are required since they require less computation time. To address the issue, in this paper we propose Soft Constrained Globally Optimal Resource Allocation mechanism that makes the choice more optimal by revisiting the previous resource allocation decisions and tries to find a solution that is globally beneficial.

III. DESIGN OF PROPOSED SOFT-GORA

The representation of the resource allocation problem is much closer to the CSP [33] and a solution can be found more rapidly than via linear programming methods that are sometimes used in resource allocation problems [33], [34]. Therefore, the resource allocation problem in this research is formulated as a variant of CSP, where the restrictions are relaxed to an extent such that the problem becomes solvable. In large networks, as the number of wireless links increases, the problem becomes intractable due to numerous combinations being generated with multiple supported channels and satisfy-able constraints. Therefore, CSP issues are usually solved through backtracking search algorithms [35]. The backtracking search algorithm minimizes complexity and helps to prune non-promising solutions that do not need to be searched. Other alternatives are only tried if the current selection leads to failure.

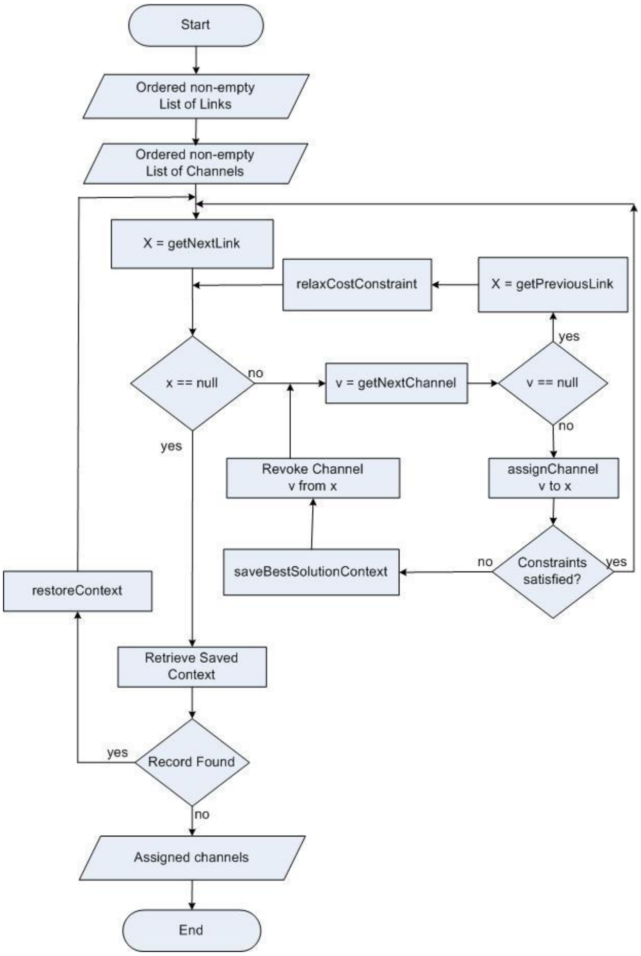

FIGURE 1. **Flowchart of Soft-GORA.**

Figure 1 shows the flowchart for working of the backtracking search algorithm when allocating a channel in a search tree. The flowchart starts with two ordered lists as inputs for bottleneck links and channels. Each link in the list is iteratively checked for allocation of a better channel. The first channel that has the best minimum cost is selected and tentatively allocated to the bottleneck link in the search tree. After its allocation, it is checked against the hard constraints. If it satisfies the constraints, the same process is repeated for the next bottleneck links. However, in case of violation of the constraints in tentative allocation, the selection is revoked and removed from the search tree. Meanwhile, the revoked channel is saved in a data structure of best available procedures. After removal of the conflicting channel, the next available one step higher cost channel is tried in a similar way. In the end, the best available channel that is considered globally most suitable is taken back from the best available data structure. The process is repeated until all the links are tentatively allocated a channel. The final output is then converted from tentative to final selection.

IV. SOFT-GORA MODEL

The classical CSP is defined as a triple of X, D and C;

- $X = \{x_1, \ldots, x_n\}$
- $D = \{d_1, \ldots, d_n\}$
- $C = \{c_1, \ldots, c_n\}$

where X is a set of variables and each of the variables needs to be assigned a value from a non-empty and a finite set of domain D according to a set of constraints C. The constraints are unary and binary; the unary constraint is a subset of relevant domain values D that are permitted under that constraint. However, the binary constraint is a subset of the Cartesian product of domain values belonging to the two neighbor variables that are permitted simultaneous assignments. The CSP makes the constraints formulation simpler by not requiring the constraints to be expressed into linear inequalities. A complete and consistent solution for solving the CSP is one in which all the variables are assigned the values from their domains in such a way that every constraint is satisfied [36].

Formulating the resource allocation problem to the CSP; the variables of the CSP directly correspond to communication links that need to be assigned with wireless channels. The supported channels form the values of the domain that each link can take. The constraints refer to the acceptable Channel Quality (CQ) and utilization ratios that a channel can support. The solutions to CSPs are found by searching through the potential assignments of channels for wireless links.

A. SOFT-GORA SCHEME

The goal in solving resource allocation problems is to find an optimal or near-optimal solution for all the links in a wireless network. In the process of assigning channels, if no optimal solution is found, then a random selection is made [23]. Sometimes, the random selection may have severe conflicts with neighboring assignments, which may degrade the performance of the network. The objective of this scheme is to loosen up some of the restrictions and search for a feasible solution that is near-optimal. In solving the classical CSPs, the goal in general is to find a feasible solution. This can include assigning channels to the wireless links in such a way that every constraint is satisfied. However, the resultant feasible solution may not be locally optimal. Therefore, to achieve both of the goals, an extended satisfaction framework is used that includes the definition of soft constraints. For soft constraints, the proposed approach uses an ordered list of wireless links that need to be assigned the new channels and the ordered list of the supported channels.

This solves two purposes as follows:

- **Link Ordering:** The ordered wireless links allow the solution to deal with hard cases first. In literature, different methods have been employed to sort these incident links. For example, Riggio *et al.* [23] made use of the delay that is calculated using the Expected Transmission Time (ETT). However, in the event of network saturation, the author has used comparison of traffic ratio deviation with a threshold. In another link-ordering approach, Juraschek [37] has used link quality as a measure that is calculated through Expected Transmission Count (ETX). Avallone *et al.* [38] used existing traffic flow given by its maximum channel capacity divided by the links in the collision domain to prioritize the links. Furthermore, Ahmad [12] has ranked the links based on the numbers of downstream nodes that use the same incident links to reach to the sink.

- **Channel Ordering:** The ordered channels permit choosing the optimal solution first. For ordering of channels, a cost is associated with each channel. Riggio *et al.* [23] have considered channel condition (measuring through channel utilization) as a parameter to measure the cost of a channel. Similarly, Juraschek [37] proposed the use of channel occupancy to measure channel conditions. The Bit Error Rate (BER) has also been used by Deng *et al.* [39] for measuring the channel condition.

The search algorithm for constraint satisfaction is provided a static ordering of wireless links and the channels; both orderings are specified before the search begins and are not changed thereafter. The ordered list of wireless links is used primarily to find the solution of the links that are more saturated and are causing throughput degradation [40]. By using the ordered list of channels, the optimum selection of a channel is made from the available values of the domain that also fulfills all the constraints. If the current partial solution does not lead to a complete solution, the algorithm tries to loosen up the constraint of the last assignment (which does not fall into the hard category of the link ordering). Thus, the least conflicting and feasible solution is recommended for the least saturated links that do not have any non-conflicting option.

1) CONSTRAINTS MODELING

A complete and globally consistent solution is found by achieving the local consistencies. The local consistency is related to the consistency of the subsets of wireless links. The local consistencies progressively realize global consistency; however, during advancement, if the algorithm fails in attaining the local consistency the constraints are reassessed. Two types of constraints are defined: (i) hard constraints and (ii) soft constraints. The hard constraints enforce the same restrictions each time and thus generate the same results. However, in the case of the soft constraints, the restrictions are softened and the aim is to obtain a different solution that is as optimal as possible. The soft constraints are associated with a cost that represents the preference of the constraint that is being satisfied. The cost is made available in the form of maximum and minimum costs, where the maximum cost means that it is maximally forbidden and the minimum cost represents maximal acceptance. Even though constraints in CSP do not have to be numerical, for ease of understanding, their equivalent mathematical modeling is also provided.

a: COST CALCULATION FUNCTION

To accommodate the soft constraints the extended framework (The Valued Constraint Satisfaction Problem (VCSP) framework), is used where soft constraints are perceived as a function of cost. The cost is used to define the level of preference in the available solutions that also satisfy the other available constraints. The proposed soft constraint is formed by using two sub-constraints to calculate the cost.

- **Channel Quality Constraint:** The network throughput largely depends on the wireless link quality; the link quality indicates the presence of interference that affects the transmission. The proposed approach uses the monitored link drops as a method to obtain the average channel loss to estimate the CQ as mathematically shown in Equation 1.

$$FLR^{\mathrm{Ch}} = \frac{\sum_{i=0}^{r} m_{\mathrm{r}}^{\mathrm{Ch}}}{\sum_{i=0}^{r} \mathcal{S}_{r}^{\mathrm{Ch}}} \times 100 \tag{1}$$

- The dividend represents the number of missing packets while the divisor represents the total packets sent on channel ‘Ch’ by the external radio ‘r’ over a particular period of time. An acceptable frame loss depends on the type of data being transmitted, but the typical frame loss ratio is less than 30%. Hence, this constraint restricts the proposed solution to only use the channels with $0 < \mathrm{FLR} < 30\%$.
- **Channel Utilization (CU) Constraint:** The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol has a natural tendency to mitigate the Co-Channel Interference (CCI), even if the interfering nodes are not in the carrier sensing range of each other. However, in multi-rate networks (external networks), the IEEE Distributed Coordinated Function (DCF) sometimes fails to provide airtime fairness to all the medium contenders and maximum achievable throughput remains limited [41]. The CU constraint restricts the algorithm for choosing over-utilized channels. The proposed approach uses the CU field of the Basic Service Set (BSS) load element of the beacon frame as its measure of channel usage. Equation 2 mathematically represents the calculation of CU by the external networks.

$$CEU^{Ch} = \frac{\sum_{i=0}^{r} CEU_{\mathrm{r}}^{\mathrm{Ch}}}{r} \tag{2}$$

The IEEE specification defines the CU as the percentage of time that is scaled to 255 which represents 100% [42]. The channel whose CU tends more towards the zero is considered as a preferred channel. The channel cost is calculated by combining both the constraints represented in Equations 1 and 2. To tailor the solution according to the situation and provide due weight to CU and CQ, the adjustment factor $'a'$ is supplied as represented in Equation 3.

$$\mathrm{Cost}^{Ch}(x) = a\,\mathrm{CEU}^{Ch}(x) + (1-a)\,\mathrm{FLR}^{Ch}(x) \qquad (3)$$

The above equation represents the cost of a channel at node ‘x’. To calculate the cost of a link ‘l’ that is formed by nodes ‘x’ and ‘y’, the average cost is calculated using costs of both the nodes as represented in Equation 4. The channel with minimum cost that also satisfies other constraints is selected as a new channel of the target link. However, the newly-selected channel should also be better than the previous channel. Therefore an additional constraint needs to be satisfied, as represented in Equation 5.

$$\mathrm{Cost}^{Ch}\left(l_{x\leftrightarrow y}\right) = \frac{\left(\mathrm{Cost}^{Ch}(x) + \mathrm{Cost}^{Ch}(y)\right)}{2} \qquad (4)$$

$$\mathrm{Cost}^{\mathrm{new}\,Ch}\left(l_{x\leftrightarrow y}\right) < \mathrm{Cost}^{\mathrm{old}\,Ch}(l_{x\leftrightarrow y}) \qquad (5)$$

b: NEIGHBOR CHANNEL CONSTRAINT

In the IEEE 802.11 CSMA/CA protocol, the Distributed Coordination Function (DCF) is used to access the wireless medium. This function has the property to deal with the situation where multiple nearby nodes contend for the same channel. This is a random-access scheme, where each node senses the medium before transmitting the data and medium is shared (airtime) between multiple nodes. However, in the presence of multiple contenders with increased offered load, the probability of sensing the channel ideal usually decreases. This constraint ensures that the newly-selected channel does not conflict with the channels of the neighbor links in the network. The mathematical formulation of this constraint is given in Equation 6.

$$Ch(l_{x\leftrightarrow y}) \notin Ch\left[\mathrm{TIL}\left(l_{x\leftrightarrow y}\right)\right] \quad \forall Ch \in \mathrm{D};\ l_{x\leftrightarrow y};\ \mathrm{TIL}\left(l_{x\leftrightarrow y}\right) \in \mathrm{X} \qquad (6)$$

Where True Interfering Links (TIL) are the subset of Interfering links that represents the list of active links of the incident link. Whereas, two-hop links are considered as interfering links. This list is maintained by Resource Allocation Server (RAS) and is periodically updated.

c: CHANNEL SEPARATION CONSTRAINT

The two links produce Adjacent Channel Interference (ACI) if both are assigned the adjacent frequencies. The adjacent frequencies cannot be used anywhere within the interference range of a transmitting node. The cause of ACI is the energy leakage of the signal from one frequency to an adjacent frequency. To minimize the effect of such interference, careful resource allocation designing is required. The channel overlap utilization is derived from the interference factor (I-factor) Ali *et al.* [43] that represents the extent of overlap between the two adjacent channels. In 802.11b based radio, the adjacent interference received on channels 1 to 11 for transmission on channel 6 is represented in Table 1. For 802.11b non-overlapping channels e.g. channel 1, 6 and 11, this value is 0. The separation of channels is represented in Equation 7 according to Table 1.

TABLE 1. **I-factor representing SNR to adjacent channels [43].**

Channels	1	2	3	4	5	6	7	8	9	10	11
SNR	0	0.22	0.60	0.72	0.77	1.0	0.96	0.77	0.66	0.39	0

$$|Ch - \widetilde{Ch}| > 4 \quad \forall Ch,\ \widetilde{Ch} \in \mathrm{D} \qquad (7)$$

where ‘Ch’ is the candidate channel for incident link and ‘$\widetilde{Ch}$’ is the channel(s) already assigned to neighboring link(s) in the interfering range of the target link. This constraint also enforces the restriction that two radios’ interface of a single node will not be assigned the same channel.

d: SINGLE CHANNEL PER LINK CONSTRAINT

The radio interfaces of transmitting and receiving nodes can only communicate with each other if both the interfaces of the nodes are tuned to the same channel [44]. This constraint is represented as assigning a single channel from domain D to a single link between two interfaces of the nodes as represented in Equation 8.

$$\sum_{k=0}^{n} l_{x\leftrightarrow \mathrm{y}}^{\mathrm{Ch}} = 1 \quad \forall Ch \in \mathrm{D};\ l_{x\leftrightarrow y} \in \mathrm{X} \qquad (8)$$

However, practically, both nodes ‘x’ and ‘y’ tune their radio interfaces to the Common Channel (CC) ‘Ch’ separately for creating their respective unidirectional links. Thus, the theory in Equation 9 should also hold true.

$$\mathrm{l}_{\mathrm{x}\rightarrow\mathrm{y}}^{\mathrm{Ch}} = \mathrm{l}_{\mathrm{y}\rightarrow\mathrm{x}}^{\mathrm{Ch}} \quad \forall Ch \in \mathrm{D};\ \mathrm{l}_{x\rightarrow y}, \mathrm{l}_{y\rightarrow x} \in \mathrm{X} \qquad (9)$$

e: CHANNELS PER NODE CONSTRAINT

The number of channels that can be assigned to a node is always less than or equal to the number of radio interfaces mounted on the node [30]. Equation 10 represents this constraint mathematically. The ‘x’ represents the node and ‘r’ is the number of radios on the node.

$$\sum\nolimits_{Ch=0}^{D} x^{Ch} \le x^{r} \quad \forall Ch \in \mathrm{D} \qquad (10)$$

2) SOFT-GORA COMPUTATION

The multi-radio conflict graph is transformed into a search tree. The multi-radio conflict graph was formulated from a multi-radio connectivity graph where the vertices represent the links between the multiple radio interfaces of the node [23]. The search tree is formed by critically selecting the vertices of the multi-radio conflict graph on which the traffic is saturated. Figure 2 represents an example of a search tree where the leaf levels represent the wireless links (selected vertices of the multi-radio conflict graph) to whom the channels are to be assigned; whereas, the leaves are the supported channels from the domain of the wireless links. However, both the supported channels and the wireless links are ordered according to the cost constraint and the criticality

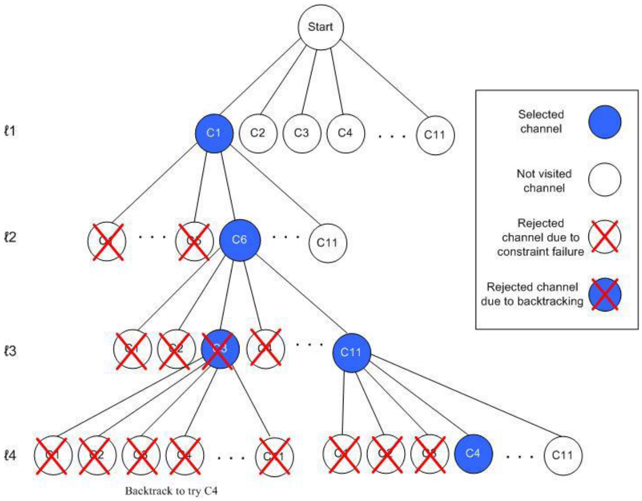

FIGURE 2. An example search tree.

ratios respectively as discussed in Section 4.1.1 above. This example represents two cases as follows:

- Local consistency failure due to failure of the constraint(s);
- Local consistency failure due to backtracking.

The first case occurs when the algorithm searches for the channels and rejects the options due to failure of one or more constraints. This is prevailed over by trying the next available option of channels. The second case takes place when all the possible options have been tried and all have failed; in this situation, the algorithm backtracking to the previously-successful selection. It is then also marked as rejected and the next possible option is tried. However, while dealing with both cases, the algorithm additionally maintains a data structure for maintaining the least constraint failing option at each leaf level. When one hundred percent backtracking is checked and no other option is available, the stored value in the data structure is brought into use at the point where the constraint fails. This also helps in minimizing the cost of the whole search tree.

B. SOFT-GORA ALGORITHM

The classical brute force algorithm works in a systematic way by generating all possible assignments of the channels to the wireless links one by one. The maximum number of permutations required to completely trace the multi-radio search tree is mathematically represented in Equation 11.

$$\text{Maximum Permutations} = \mathrm{D}^{\mathrm{X}} \tag{11}$$

D represents the total number of supported channels and X is the total number of wireless links that correspond to the CSP domain values and variables respectively. Considering C constraints, the total number of tests that will be checked by the search algorithm will also increase. Equation 12 represents the brute force algorithm complexity.

$$f(\mathrm{X}) = \mathrm{O}(\mathrm{CD}^{\mathrm{X}}) \tag{12}$$

However, in larger wireless networks as the number of repairable wireless links (X) tends to increase, the problem becomes intractable. In this work, a backtracking-based search algorithm is used that helps to prune the non-promising options that do not need to be searched. The search starts from the most-saturated links and moves towards the least-saturated links, trying to make the partial solution complete and consistent. During the systematic working of the search algorithm, it is often impossible to find a solution when the domain turns out to be empty. In this case, the solution is declared as infeasible and the algorithm reconsiders the last assignment of the channel and tries the next least cost solution accordingly. This is achieved by means of backtracking. At any stage of the channel selection, the domain consists of two parts: (i) a subset of channel(s) that already have been rejected due to constraints failure (local consistency) or due to backtracking (global consistency), and (ii) a subset of channel(s) that still needs to be checked. The backtracking continues until all the wireless links are assigned with the channels while satisfying the constraints.

Algorithm 1 Backtracking Resource Selection Algorithm

Input: *Ordered list of Wireless Links (X), Cost Constraint based ordered list of Supported Channels of X (Domain), Constraint Functions*

```
function Multi-radioSearchTree(int currentLevel)
    x = getNextLink()
    BacktrackLeafLevel = currentLevel
    for each $v \in Domain(x)$ do
        assignChannel(x, v, currentLevel)
        if checkConstraints(x, v, currentLevel) then
            relaxConstraint = false
            BacktrackLeafLevel = Multi-radioSearchTree(currentLevel+1)
        end if
        savebestSolutionContext(BacktrackLeafLevel, x, currentLevel)
        revokeChannel(x, v, currentLevel)
        if BacktrackLeafLevel < currentLevel then
            return BacktrackLeafLevel
        end if
    end for
    BacktrackLeafLevel = getBacktrackLeafLevel(x, currentLevel)
    if (BacktrackLeafLevel > 1) then // check more to backtrack
        relaxConstraint = true
        return BacktrackLeafLevel
    else
        if any context saved then
            Multi-radioSearchTree(restoreContextLevel)
    end if
end function
```

The backtracking search algorithm presented in Algorithm 1 requires list of wireless links (X), cost constraint based ordered list of supported channels of X (domain); and constraint functions as inputs. The root of the search tree is declared as the first level, and each level below represents the links that need to be assigned with the channels. Therefore, the second level is the first bottleneck link. The domain of link represents the ordered list of channels with respect to their costs. The least cost channel is the first channel. The algorithm first checks feasibility by tentatively assigning a channel. The channel is withdrawn from any assignment in two cases: first, if it violates the hard constraints (line 6); and second, if a backtracking is done (lines 17-19) and a value is returned (line 8). After each tentative assignment (and before revoking it), a data structure is maintained for recording the context of the best least cost channel. This best cost solution is then brought into use, provided there is no such channel available that completely complies with the constraints (lines 21-22).

V. SIMULATION AND ANALYSIS OF RESULTS

The implementation of Soft-GORA is carried out in a simulation environment using OMNeT++ [45]. In order to validate the proposed approach, the simulation results are compared with Interference and Traffic Aware Resource allocation(ITACA) by Riggio *et al.* (2011) and External Interference Aware Resource allocation(EICA) by [23] and [37]. The ITACA and EICA consider the possibility of co-located networks in addition to internal interfering links. For selection of priority links, the ITACA employs delay and hop distance as basic parameters where the traffic is evenly distributed; however, an additional parameter of traffic intensity is considered in the case of saturation. Furthermore, the Expected Transmission Count (ETX) is used in EICA for assignment of priorities to the critical links. For assessment of channels, both the ITACA and EICA consider 2-hop neighbors as interfering links; however, for co-located networks ITACA uses CU while EICA uses channel occupancy. In comparison with the existing work, the efficiency and performance gain of proposed approach is ensured by deploying homogeneous simulation setups, with respect to nodal density, radio, packet size and etc. Different factors can affect the simulation results, therefore, the consistency and reproducibility of proposed work is determined through repetitive analyses of multiple traces obtained through ten runs of each scenario. The details of simulation parameters are presented in Table 3. During the experiments, different scenarios are considered by varying the traffic flow rate and the nodal density.

A. EXPERIMENTAL ANALYSIS

The simulation experiments are conducted in a multi-hop environment to measure the performance of the proposed approach. In the first experiments, the achieved throughput is compared by varying the number of hops. The impact of variation of traffic flow on the throughput is examined in the second set of experiments. The third experiment analyzes the effect of end-to-end delay in presence of different concurrent flows. In the last, the nodal density is varied to investigate the packet delivery ratio (PDR).

TABLE 2. Performance comparison table.

Scenarios	Performance Metrics		EICA	ITACA	Soft-GORA
Varying Channels Analysis	Delay (Sec)	minimum	0.45	0.39	0.25
		maximum	1.12	1.03	0.76
		average	0.77	0.68	0.51
	PDR (%)	minimum	51.26	57.25	67.44
		maximum	95.31	97.53	98.91
		average	78.15	79.36	87.52
Nodal Density Analysis	PDR (%)	minimum	45.36	51.78	78.29
		maximum	95.31	97.53	99.00
		average	71.36	76.35	92.36
Flow Variation Analysis	Delay (Sec)	minimum	0.25	0.23	0.18
		maximum	0.84	0.77	0.39
		average	0.36	0.33	0.23
Hop Variation Analysis	Throughput (Mbps)	minimum	1.57	1.98	3.50
		maximum	6.66	6.68	6.77
		average	2.98	3.51	4.99

TABLE 3. Simulation parameters.

Parameters	Values
World Size	1000m x 1000m
No. of nodes	20, 40, 60, 80, 100
Traffic Type	UDP
Packet Size	512 Bytes
Physical Standard	IEEE 802.11a
Physical Transmission	Fixed at 12Mbps
Channels	12
Traffic Load	CBR
Traffic Flow	5-14 for 20 nodes
Data Rate	100 pps
No. of Radios	3
Simulation Duration	3700 Seconds
Interference Estimation Cycle	Every 10 Minutes
Interference Estimation Duration	3 Seconds
Management Frame Cycle	Every 100 ms
Resource allocation Cycle	Every 10 Minutes
Channel Switch Delay	0.03 Seconds

B. PERFORMANCE EVALUATION

Three performance metrics achieved throughput, delay and PDR are considered to evaluate the proposed approach [23], [46]–[51]. Table 2 summarizes the performance, while detail discussion is presented in the following sections.

1) THROUGHPUT

The throughput comparison in the multi-hop environment helps to effectively model the interference influence on wireless links. Twenty one nodes scenario is considered in this experiment; out of which one is devoted as a gateway (the sink) and the remaining twenty nodes acts as ordinary

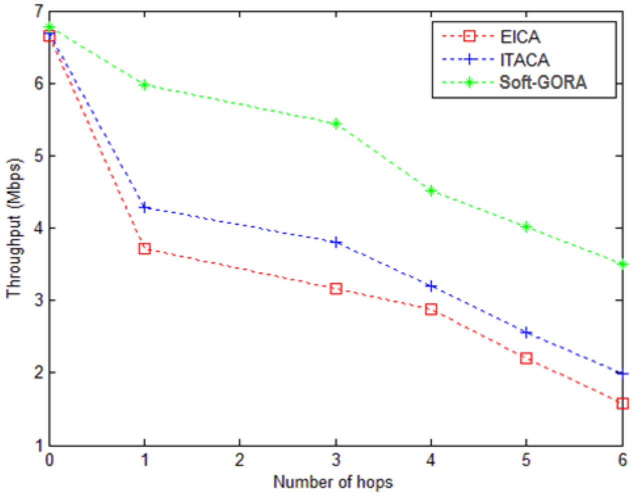

FIGURE 3. Throughput Effect Vs. Nodal Density.

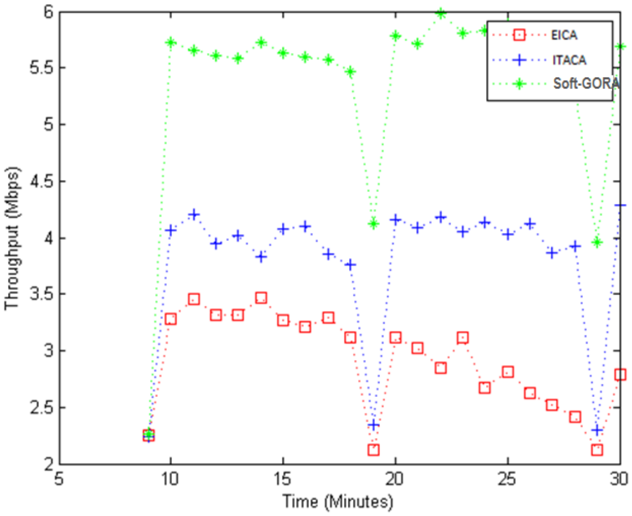

FIGURE 4. Achieved Throughput over Time.

nodes. Twelve random flows are initiated between the sink and sources.

The graph for comparison of average throughput is shown in Figure 3, where the throughput at one hop distance remains almost alike but as the distance between the sources and sink increases, it critically affects all the three approaches. The increase in distance from source to sink also increases the possibility of collisions and interference between multiple hops. However, beyond 2-hop distance, the throughput in Soft-GORA is considerably high. The achieved throughput by Soft-GORA, ITACA and EICA is 5.03Mbps, 3.75Mbps and 3.35Mbps respectively. This shows that Soft-GORA obtained 34.13% and 50.14% higher performance than ITACA and EICA respectively in terms of achieved throughput. The reason for achieving high throughput is the fact that the bottleneck links are assigned the best possible channels keeping in view the global cost. This shows that Soft-GORA in the multi-hop environment gives better output.

Fig. 4 shows the second experiment, where the measured throughput at 3-hops is plotted over time. The graph shows sudden downward spikes around the 10th, 20th and 30th minute. These oscillations are due to the sensing mechanism for interference estimation that is turned on every ten minutes. During this time, one of the radio interfaces becomes inactive for traffic forwarding for almost 3 seconds. However, to minimize the effect of packet drops or delay, link redirection mechanism is implemented as discussed earlier. This slightly lowers the performance, but in terms of performance gain, this is negligible.

To prove the optimal distribution of channels to the priority links, the effect of varying traffic loads on network performance is examined in the third experiment. The same twenty nodes topology is taken into consideration; however, to idealize the effect of varying flows, different nodes were activated at different timings. During this, the non-activated nodes act as relaying nodes that forward data of other active nodes. At different timings, five to fourteen out of twenty nodes were activated.

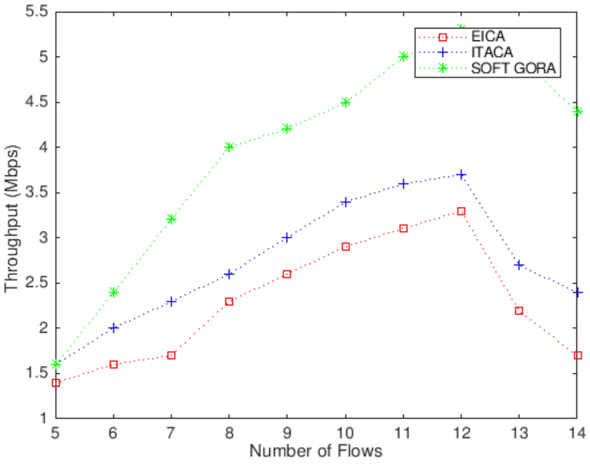

FIGURE 5. Throughput Effect Vs. Flows.

Figure 5 represents the above discussed scenario, where the throughput from flows five to fourteen increase in a linear fashion in both the benchmarked approaches ITACA and EICA; whereas, the trend in Soft-GORA graph is more polynomial. During this time, the increase in flows also gives higher throughput because the data delivery is done through a scattered network where the inter-flow interference is much less. This ultimately provides more bandwidth to the flows for simultaneous transmissions. The throughput behavior at flow 13 is quite different in Soft-GORA; the Soft-GORA gained a slight increase in throughput and was sustained, whereas the ITACA and EICA both faced a sudden decrease in throughput. However, at flow 14, the throughput decrease is also witnessed in Soft-GORA but still the curve is smooth and Soft-GORA still achieved considerably higher throughput than ITACA and EICA. This demonstrates that Soft-GORA dealt more effectively with the network saturation.

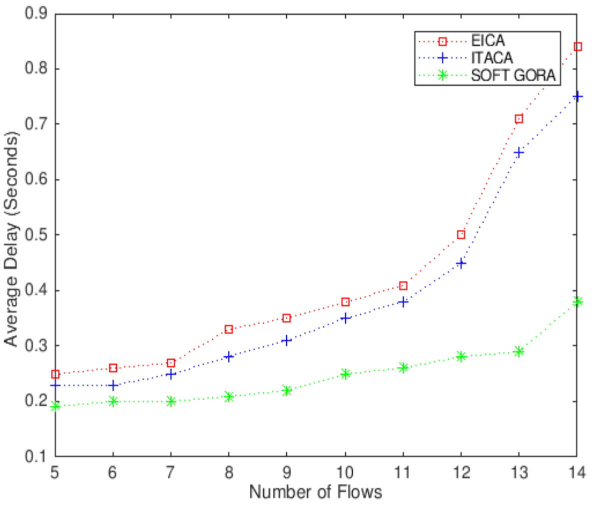

FIGURE 6. End-to-End delay Vs. Flows.

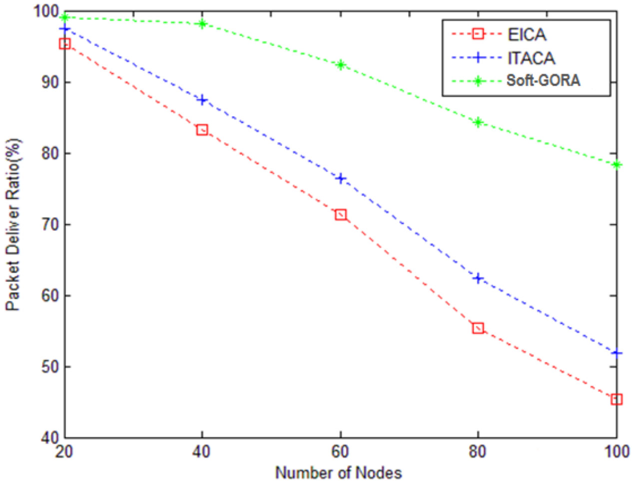

FIGURE 7. PDR Vs. Nodal Density.

The achieved throughput by Soft-GORA is 3.91Mbps while ITACA and EICA achieved only 2.73Mbps and 2.32Mbps respectively. This shows that the performance achieved by Soft-GORA is 43.22% and 68.53% higher than ITACA and EICA respectively in terms of throughput.

2) END-TO-END DELAY

this experiment is performed to analyze the consequence of interference and saturation under varying traffic loads. As discussed in the previous section, the topology of same twenty one nodes is considered. Figure 6 represents graph of end-to-end delay in comparison with the varying flows where the delay variation in both proposed approach as well as benchmarked approaches remains almost similar until flow 7, however, afterwards this variation slightly increase until flow 12. The reason is that the data delivery is done through a scattered network where the inter-flow interference is much less. This ultimately provides more bandwidth which helps in carrying simultaneous transmissions. After flow 12, a momentous variation can be witnessed. However, from flows 12 to 14, the increase in delay is abrupt in ITACA but smooth in Soft-GORA. This signifies that Soft-GORA comparatively reduced the effect of interference by assigning better channels in the interfered region. The average delay faced by Soft-GORA is 0.25 seconds, whereas, the ITACA and EICA faced 0.39 seconds and 0.43 seconds respectively. This clearly shows the effectiveness of Soft-GORA as it more effectively catered the interference effect by an aspect of 35.89% and 41.86% than benchmarked approaches, ITACA and EICA respectively.

3) PACKET DELIVERY RATIO

This experiment is performed to measure the packet delivery ratio (PDR) in comparison with the varying nodal densities. The interference and nodal density both have unwanted affect the PDR. The active nodes are kept half of the total nodes in the field. The PDR is generated from the profile maintained at the sink (wired entity). The PDR graph in Figure 7 represents that, at the small scale network, all the three approaches behave almost in a similar fashion and achieved the delivery ratio of 95%. However, the increase in nodal density, from 20 to 40, decrease the PDR to 98.12%, 87.52% and 83.29% respectively for Soft-GORA, ITACA and EICA. The reason behind this drop is the increase in the routing overhead, collision occurrences and saturation in the network. The Soft-GORA performed better even though the nodes were doubled; however, the onward increase in the number of nodes also affected Soft-GORA. The achieved average PDR of Soft-GORA is 90%, while the ITACA and EICA achieved around 75% and 70% respectively. This shows that the packet delivery achieved by Soft-GORA is higher than ITACA and EICA by the factor of 20.38% and 28.91% respectively.

VI. CONCLUSION

This research work proposes a dynamic backtracking search-based resource allocation scheme (Soft-GORA) for IoT backhaul communication. The main focus of this research is to improve the IoT networks performance in multi-hop deployments by assignment of best available channels that have globally minimum cost. The resource allocation problem is modeled as a soft constraint satisfaction problem; the cost constraint is relaxed to an extent where the solution becomes available, while still satisfying the hard constraints. The simulation results reveal improvement in performance achieved by Soft-GORA in dense multi-hop networks. The results of the throughput in multi-hop flows indicate that

Soft-GORA performs higher than ITACA and EICA by the factor of 34.13% and 50.14% respectively. In the case of varying traffic load, the results show that Soft-GORA excels with 43.22% and 68.53% higher throughput and approximately 35.89% and 41.86% less delay than ITACA and EICA respectively. Similarly, in scaled networks, the Soft-GORA delivered packets almost 20.38% and 28.91% better than ITACA and EICA respectively. The real test-bed implementation would better reveal the performance of the proposed approach, however, due to time and budget factors, it has been left as future work. Additionally, the proposed scheme will be further enhanced in the context of cross-layer.

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