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Search and routing in large area hierarchical IoT networks

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Abstract: The world wide use of the public internet has opened up the possibility of applying similar technology for automated functioning of physical objects equipped with micro electronic devices. The perception is to apply that kind of technology to various areas of human activity for enhancing the quality and scale of performance. Starting from automated homes, the possibility of application are projected to be in efficient transport systems, energy management, smart cities, industrial automation, environmental monitoring, business management, defence operations etc. Such activities require huge network support, deployed over vast areas of the globe with suitable taxonomy for fast connectivity and operation. In this paper, it is suggested that the network is hierarchical having hybrid tree graph architecture, with the root node as the overall controlling headquarter. The hierarchy of the nodal stations is assumed to be based on the geographical distance from the root node, in which the nodes having the same hierarchy are also linked by collateral bus connectivity. The search of a node and routing data to the destination is carried out along a path which is as close as possible along the geographical direction of the location of that destination. Such a procedure was earlier developed by this author [19], [20], accounting fully for the sphericity of the globe. Accordingly, an algorithm for the search and routing in the envisaged network is presented in conclusion.

Keywords: Internet of Things, application areas, hierarchical network, hybrid tree graph, search, routing.

1 Introduction

After the advent of the public internet and world wide web, the Internet of Things (IoT) is an unprecedented prospect for societal advance at the present juncture. Essentially an IoT means a set of objects equipped with devices like sensors/transceivers, microcontrollers and actuators connected by communication channels for some desired activity in automatic machine-machine (M2M) mode. The physical objects and the communication channels therefore form respectively the nodes and links of an IoT network. Te communication channels can be wireless or optically fiber-cabled, utilising the public internet and the attended cloud, if required. However the use of such open public utility invites security concerns, when confidentiality is paramount.

The application of IoT in different areas of activity are numerous. To name a few, the simplest is in home automation for automatic control of lighting, air-conditioning/ heating, appliances, security cameras systems etc. In transportation by road, monitoring the logistics, fleet management and activity (Luo et. al. [1], Salih and Younis [2], Porru et, al. [3]). In energy management, creation of smart grid for proficiency in production and distribution, as also for meter reading (Goudarzi [4], Shahinzadeh et al. [5], Morello et, al. [6]). In industry (IIoT), automation of machine operation and their monitoring (Boyes et. al. [7], Hazra et. al. [8], Vitturi et. al. [9], Vaclova et. al. [10]). In agriculture, monitoring soil and environmental conditions (Grimblatt et al. [11], Xu et. al. [12]); and in supply chain management (Ben-Daya et. al. [13], Abdel-Basset et. al. [14]). In military deployment of assets, surveillance and combat objectives. In healthcare too, remote monitoring of conditions of critical patients through various devices. By a cursory understanding of such systems one may also consider a network branches of corporate entities spread over the globe to similar category, except that the "things" of IoT are intelligent human beings instead of electronic devices. The above citations on the subject are few in number, but some of them are review articles containing hundreds of other references. The literature on the subject is vast owing to its potential applicability in diverse fields.

Most of the IoT networks sketched above tend to be huge, connected by a mesh of network links, spread over large geographical areas. Wireless mesh networking (WMN) in which all the nodes of the network are connected to each other, is sometimes useful. For the purpose *Inter-flow Network Coding* (IXNC) or simply Network Coding (NC) is employed (Kafaie et. al. [15]), in which more than one packet is forwarded in each transmission of data. Alternatively, *Opportunistic Routing* (OR) can also be employed, utilising the broadcast nature of the wireless medium (Akyildiz and Wang [16]). However, in a comparative study, Xu et. al. [17], find that NC does not improve throughput benefit as compared to routing. In the absence of specific restriction on the taxonomy of the network, scalability issues arise. In large networks, loops may form increasing the latency of search and communication of messages to the target destinations, making the system very complex and even chaotic with uncertain consequences.

A routing algorithm with a suitable restricted architecture for lage networks is therefore a necessity for higher throughput and reduced latency. In any case, a head node or a root is always required for controlling the specified network. As the IoT networks tend to be large in size, spread geographically over the globe, mostly employing fiber-optic communication channels, some decentralisation is imperative, with partial decision making power authorised to lower level nodes. This means that a hierarchical classification among the set of nodes of the network is created for acquisition and transmission of signals for desired activity at the destination nodal object. Mathematically, the taxonomy of such a network should have a tree-like architecture with some additional features. Here it is suggested that the nodes having the same hierarchy are also linked together for collateral transmission of data for connectivity with the destination node, averting a path through the root node for every connection. The classification of hierarchy of nodes can generally be based on the geographical spread of the nodes, irrespective of their activity. Accordingly, with the root node as the head quarter of all the activities, the closest nodes form the first tier, the string of nodes next in distance from the root, forming the second tier and so on. The lower level nodes must be connected to some of the higher level nodes as in a usual tree graph. Additionally, as stated before, the nodes on the same tier of hierarchy are assumed to be inter-connected. Every node passive or active is assumed to perform some specific tasks. The software driving the network must provide an operator, who may be mobile, to log on to the nearest node of the network in order to search and monitor the tasks at some other destination node and activate it if necessary. The connectivity in such networks is actually possible by the Prim-Jarvik Minimum Spanning Tree algorithm (Ahuja et. al. [18], p. 523). This algorithm, though greedy, is planer raising question for applicability in large networks. Moreover, the algorithm does not account for the sphericity of the globe. In this paper, a greedy spherical connectivity is used following Bose [19], [20]. The search and connectivity of the destination node is carried out in the lower or higher tiers of the network from the current nearest neighbour node. If connectivity from the current source node is not successful, it is carried out from its nearest neighbour nodes in succession till the destination node is located. The intermediate nodes lying on the path to the destination node are recorded, and use that connectivity for monitoring and/or activating the desired tasks at the end node. Full geographical sphericity formulae are used for global wide area networks (WAN) pathways

(Bose [19]), while for metro and mega-polis networks (MAN) plane geographical considerations are applied (Bose[20]). The connectivity between the far flung nodes of the network is assumed to be by means of auxiliary secure ground stations and gateways via fiber-optical and wireless links.

2 The hybrid-tree IoT routing

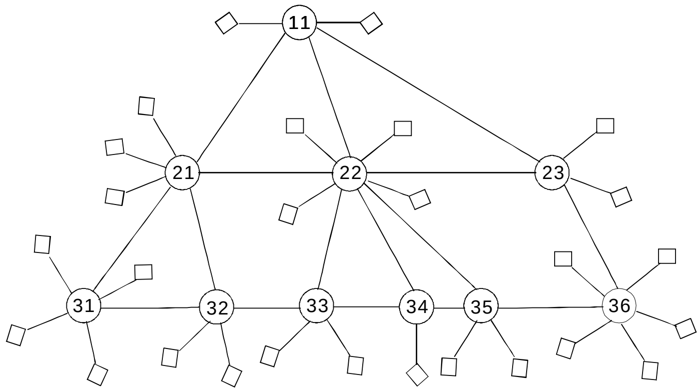

Figure 1: An IoT hybrid-tree network with 10 nodes and 27 leaves.

A very small scale schematic hierarchical IoT network is shown in figure 1. The hierarchical order enables the nodes or the stations to be arranged in tiers of an array, shown by circles and labelled as such by paired indices. The nodes perform certain specific tasks represented by *leaf nodes* (Coreman et. al. [21]) shown as squares. The bus connects of the nodes having the same hierarchy, makes the otherwise tree graph taxonomy of the network as a bus-tree graph. An operator, privy to monitor some of the tasks represented by the leaf nodes, can log to the nearest nodal station in order to reach the destination node using the intermediate ones at lower or higher level using the shortest links.

As the nodal stations are spread over a large geographical area, on a metropolitan/mega-polis (MAN) or on a global scale (WAN), the stations require large number of auxiliary intermediate stations for connectivity, increasing latency and costs in the transmission of signals. The selection of the path from source to destination is kept closest to the straight line joining the two in the case of MAN (Bose [20]) and the great circular arc or the geodesic in the case of WAN (Bose[19]).

The nodal stations are labelled by paired indices $[i,\, j]$ as shown in figure 1, where $i = 1,\, 2,\, 3, \cdots,\, i_n$ and $j = 1,\, 2,\, 3, \cdots,\, j_n$, the root being $[1,\, 1]$. The limit i_n is fixed for the network; its value is 3 in figure 1; whereas j_n depends on the hierarchy i. In figure 1, for instance, if $i = 2$, $j_n = 3$, and if $i = 3$, $j_n = 6$. The leaf nodes on the other hand, can be labelled by a single index l, where $l = 1,\, 2,\, 3, \cdots,\, l_{max}$, the value of l_{max} depending on the node $[i,\, j]$. For instance, if the node is $[2,\, 1]$, $l_{max} = 3$ and if it is $[3,\, 6]$, $l_{max} = 5$. The search operation is initiated from the nearest available station A_1 with the label $[i_1,\, j_1]$ to seek the destination A_n having the label $[i_n,\, j_n]$, scanning the nodes row-wise moving downwards or upwards along the branches of the tree according as $i_1 < i_n$ or $i_1 > i_n$, keeping the path as close as possible to the direction of the destination. If a connecting link is not found the initial search is shifted to the right or left of $[i_1,\, j_1]$. The nodes so found are indexed as $m = 1,\, 2, \cdots,\, i_n$. In as much as these stations may be widely separated by distance, the linking requires the support of other auxiliary nodes along the puported near optimal path.

All the nodes whether belonging to the main network or the auxiliary ones along the connectivity path are assumed to possess their latitude and longitude from GPS data. Let the latitude and longitude of the source A_1 and A_n be (ϕ_1, λ_1) and (ϕ_n, λ_n) respectively and a the shortest terrestrial angular distance between them subtended at the center of the globe. This means that a is the great circular arc joining the points A_1 and A_n and hence (Bose [19])

$$\cos a = \sin\phi_1 \sin\phi_n + \cos\phi_1 \cos\phi_n \cos(\lambda_n - \lambda_1) \tag{1}$$

If the angular distance a does not exceed 1.5^o, the topography of the ground can be treated as a flat surface. As the radius of the earth is 6357 km, this angle would be nearly 166 km in length that can be covered by a circular area of nearly 21754 sq. km or 8400 sq. miles - an area equalling the area of the largest mega-polis of the world. In this simplified case, deviation from the geographical north serves the purpose of the search (Bose [20]). Let θ_n be the deviation of the destination A_n from the geographical north, as viewed from A_1 , then as in Bose [20] it can be proved that

$$\theta_n = \arcsin\Big[\frac{\cos\phi_n \sin(\lambda_n - \lambda_1)}{\sin a}\Big] \tag{2}$$

As the search progresses from one node to the next, options are available for the choice of nodes. Suppose that from a node A_i $(i = 1, 2, 3, \cdots, n-1)$ a node A_k $(k = 1, 2, 3, \cdots, k_{max})$ is to be selected, then if the deviation of A_iA_k from the north is θ_k, then the deviation of A_k from A_n is

$$\chi_k = \theta_k - \theta_n \tag{3}$$

Then, for the shortest linked path

$$z_k = |\chi_k| \tag{4}$$

must be minimum. The use of auxiliary stations can put additional cost C_k which does not exceed a certain maximum value C_{max}. In that case, the shortest path is obtained by minimising the objective function

$$z_k = p|\chi_k| + (1-p)\, C_k/C_{max} \tag{5}$$

where p is a fractional priority to be accorded to the direction of the destination.

In the alternate case when the source and destination nodes are separated on a global scale, the sphericity of the earth leads to a formulation like that in Bose [19]. In that method, the shortest path joining these two stations is kept close to the great circular arc (geodesic) joining A_1 and A_n, through intermediate stations A_k $(k = 1, 2, \cdots, k_{max})$. Hence if the angular measure of A_k from a node A_i with respect to the geodesic joining A_i and A_n is $\chi_k = \angle A_kA_iA_n$ given by

$$\chi_k = \arcsin\Big[\frac{\cos\phi_n \sin(\lambda_n - \lambda_1)}{\sin a}\Big] - \arcsin\Big[\frac{\cos\phi_k \sin(\lambda_k - \lambda_i)}{\sin a_{ik}}\Big] \tag{6}$$

where

$$\cos a_{ik} = \sin\phi_i \sin\phi_k + \cos\phi_i \cos\phi_k \cos(\lambda_k - \lambda_i) \tag{7}$$

The shortest linked path of the stations is given by minimisation of z_k as given by Eqs. (4) and (6). For selection of the auxiliary nodes linking two stations of the IoT network, Eq. (5) is to be employed instead of Eq. (4).

3 The Algorithm

The method described in the preceding section leads to the following pseudo-code for for quick connectivity with the destination node for the desired action at that node. The desired action is designated as the character constant "ACTION", which is displayed/automated when the corresponding character variable named ACTION_VARIABLE holds true. In the algorithm, the latitude and longitude of the stations of the IoT are named as ϕs and λs, while those of the auxiliary nodes linking any two stations of the network are respectively named as ϕ and λ. Similarly, θs and θ denote the deviations of the two types of stations from the Northward direction for use in the planer case. The algorithm is divided in to two parts. In the first part, which is static, the nodal stations of the path joining the source to destination are identified. In the second part, an actual command for action at the destination node is transmitted for the performance of the given action. The search of the nodal stations for the optimal path is carried out downward or upward according to the destination being in lower or higher hierarchy. If no direct connection is possible from the closest station, the search is shifted to the nearest station to the right or to the left of the starting source. A counter named kount is used for that purpose, which alternatively takes up the values 1, 2, 3, ... as may be necessary. The odd numbered ones lie on the right hand side of the user's station of origin at increasing distance, and the even numbered ones similarly lie on its left hand side.

Algorithm. Fast Linked IoT Routing.

1. Input: i_{max} \\ Number of tiers of the network.
$\phi s[\,,\,], \lambda s[\,,\,]$ \\ Latitude, Longitude of stations of the IoT nodes.
$\Phi[\,,\,], \Lambda[\,,\,]$ \\ Latitude, Longitude of shortest path stations.
$p,\ C_{max}$ \\ Fractional prioriy of deviation from shortest geometrical/geodesic path on maximum permitted cost of a link.
$C[\,]$ \\ Alloctable cost of a link.
$\Theta[\,]$ \\ Angular deviation from North of shortest path stations.
$\theta[\,]$ \\ Angular deviation from North of auxiliary stations on a link.

2. Output. ACTION \\ String character constant for initiating a task.

$kount \leftarrow 1$ \\ Begin shortest path search from source node $[i_1,\, j_1]$ to destination node $[i_n,\, j_n]$.
$i \leftarrow i_1;\ j \leftarrow j_1$

3. $\Phi[ii] \leftarrow \phi s[i,\, j];\quad \Lambda[ii] \leftarrow \lambda s[i,\, j]$
$\Phi[n] \leftarrow \phi s[i_n,\, j_n];\quad \Lambda_n \leftarrow \lambda s[i_n,\, j_n]$
$a_{in} \leftarrow \arcsin\{\sin\Phi[ii]\sin\phi[n] + \cos\Phi[ii]\cos\Phi[n]\cos(\Lambda[n] - \Lambda[ii]\}$
if$(ii == 1)\ a \leftarrow a_{in}$
$\Theta_n \leftarrow \arcsin\{\cos\Phi[n]\sin(\Lambda[n] - \Lambda[ii])/\sin a_{in}\}$

4. for $k \leftarrow j_{min}$ to j_{max} \\ Nodes linked at the next tier.
if$(a < 1.5\pi/180)$ then
$\chi[k] \leftarrow |\Theta[k] - \Theta_n|$
else

$\phi_k \leftarrow \phi s[i, k]$; $\lambda_k \leftarrow \lambda s[i, k]$
$a_{ik} \leftarrow \arccos\{\sin\Phi[ii]\sin\phi_k + \cos\Phi[ii]\cos\phi_k\cos(\lambda_k - \Lambda[ii]\}$
$\chi[k] \leftarrow \Big|\arcsin\{\cos\Phi[n]\sin(\Lambda[n] - \Lambda[ii])/\sin a_{in} -$
$\arcsin\{\cos\phi_k\sin(\Lambda[k] - \Lambda[ii])/\sin a_{ik}\}\Big|$
end for
end for

5. for $k \leftarrow j_{min}$ to $j_{max} - 1$ \\ Sort angles χ to avoid ties.
for $l \leftarrow k + 1$ to j_{max}
if($\chi[k] > \chi[l]$) then
temp$\leftarrow \chi[k]$; $\chi[l] \leftarrow \chi[k]$; $\chi[l] \leftarrow$ temp
end if
end for
end for

6. $k_{min} \leftarrow j_{min}$
for $k \leftarrow k_{min} + 1$ to j_{max}
if($\chi[k_{min}] > \chi[k]$) $k_{min} \leftarrow k$
end for
$j \leftarrow k_{min}$

7. if($i == i_n$ or $j == j_n$) then
Go To Step 9
else
Go To Step 8
end if
$i \leftarrow i + 1$; if($i_n < i_1$) $i \leftarrow i - 1$
Go To Step 3

8. if($kount/2 * 2$ /= $kount$ && $j <= j_{max}$) $j \leftarrow j_1 + (1 + kount)/2$ \\ Look for path from a node on the right at the same tier level.
if($kount/2 * 2$ == $kount$ && $j >= j_{min}$) $j \leftarrow j_1 - kount/2$ \\ Look for a path from a node on the left at the same tier level.
$\Phi[ii] \leftarrow \phi s[i, j]$; $\Lambda[ii] \leftarrow \lambda s[i, j]$
$kount \leftarrow kount + 1$
Go To Step 3 \\ Search of optimal path completed.

9. $m \leftarrow i_1$ \\ Begin Data transmission along the shortest path.

10. for $k \leftarrow 1$ to m_{max} \\ Maximum number of auxiliary stations in the neighbourhood of station m.
$a_{mm} \leftarrow \arccos\{\sin\{\sin\Phi[m]\sin\Phi[m+1] + \cos\Phi[m]\cos\Phi[m+1])\cos(\Lambda[m+1] - \Lambda[m])$
if($a < 1.5 * \pi/180$) then
$\chi[k] \leftarrow |\theta[k] - \Theta[n]|$
else
$a_{mk} \leftarrow \arccos\{\sin\Phi[m]\sin\phi[k] + \cos\Phi[m]\cos\phi[k]\cos(\lambda[k] - \Lambda[m])$
$\chi[k] \leftarrow \Big|\arcsin\{\cos\Phi[m+1]\sin(\Lambda[m+1] - \Lambda[m])/\sin a_{mm}$
$- \arcsin\{\cos\phi[k]\sin(\lambda[k] - \Lambda[m])/\sin a_{mk}\Big|$ \\ Angle of node k with respect to node m.
end for

11. for $k \leftarrow 1$ to $m_{max} - 1$ \\ Sort angles to avoid ties.
for $l \leftarrow k + 1$ to m_{max}
if($\chi[k] > \chi[l]$) then
temp $\leftarrow \chi[k]$; $\chi[l] \leftarrow \chi[k]$; $\chi[l] \leftarrow$ temp
end if
end for
end for

12. for $k \leftarrow 1$ to m_{max}
$z[k] \leftarrow p\chi[k] + (1 - p)\, C[k]/C_{max}$ \\ Objective function to be minimised.
end for

13. $k_{min} \leftarrow 1$
for $k \leftarrow 2$ to m_{max}
if($z[k]_{min}] > z[k]$) $k_{min} \leftarrow k$
end for
$m \leftarrow k_{min}$
if($m == i_n$) then
Go To Step 14
else
$m \leftarrow m + \mathrm{sgn}(i_n - i_1)$; Go To Step 10
end if

14. for $l \leftarrow 1$ to l_{max} \\ l_{max} = Maximum number of leaf nodes at station m.
if(ACTION_VARIABLE == true) then
Output "ACTION"
Stop
end if
end for

15. end

4 Conclusion

The Internet of Things (IoT) aided by the public internet is a twenty first century emerging technology that holds prospect for tremendous facilitation in all kinds of human activity. Beginning with such simple application as in home automation, the possibilities are in transportation systems, energy management, smart cities, environment monitoring, business management, defence operations etc. The size of the networks in view can be huge, spread over the globe, with numerous nodes or stations linked in some manner, such as wireless or optically cabled. In order to minimise the cost and latency of transmission in such huge networks, a restrictive taxonomic architecture is desirable instead of Network Coding like the IXNC in which all the nodes are connected with each other for direct communication. Here in this article, it is suggested that an IoT network has a hybrid tree graph taxonomy which has a head or root node, with the other nodes globally distributed around it. The latter type of nodes are attributed a hierarchy, depending on the geographical distance from the root node, while those of the same hierarchy are collaterally linked to each other as well. The search in such a network is started from any node and the shortest path to the destination node (for some action) is sought as close as possible to the arc joining the two positions. The search is made first towards lower hierarchy, and in case of failure, towards the higher order nodes. If failure recurs again, the search is started from the nearest neighbour nodes of the same hierarchy as that of the starting source. Having found the shortest path, the routing is carried out through the nodes on the path so found. A simpler search and routing method is employed for networks spread over metropolitan and mega-polis cities using the deviation from the northward direction as a measure of deviation from the direction of the destination.

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Conflict-of-interest There is no conflict of interest involved in the reported research of this paper.

Data Availability Statement This paper uses easily available references to books and papers published in journals related to the topic.

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