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TCMCA: a source-based distributed topology control algorithm for mission critical applications in mobile ad-hoc networks

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Abstract

Topology control in a wireless ad-hoc network allows better spatial reuse of the wireless channel and network resources. The existing topology control algorithms tend to optimise network power usage by keeping the topology connected but do not take the network application requirements into account. Mission critical applications which require explicit end-to-end bandwidth and delay guarantees may not find enough resources in the network with the existing network topology. We have devised a topology control algorithm for mission critical applications (TCMCA) in wireless ad-hoc networks, which adapts the network topology to improve the available resources for a set of mission critical applications (high priority services) in a network. TCMCA is a source based algorithm where topology control decisions are made on distributed network knowledge. The performance of TCMCA is evaluated for a static wireless network and compared against algorithms such as connect, LINT and full power transmissions. We demonstrate that TCMCA shows better support for mission critical services for varying number of mission critical applications in the network.

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TCMCA : A Source-based Distributed Topology Control Algorithm for Mission Critical Applications in Mobile Ad-hoc Networks

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Abstract— Topology control in a wireless ad-hoc network allows better spatial reuse of the wireless channel and network resources. The existing topology control algorithms tend to optimise network power usage by keeping the topology connected but do not take the network application requirements into account.

Mission critical applications which require explicit end-to-end bandwidth and delay guarantees may not find enough resources in the network with the existing network topology. We have devised a topology control algorithm for mission critical applications (TCMCA) in wireless ad-hoc networks, which adapts the network topology to improve the available resources for a set of mission critical applications (high priority services) in a network.

TCMCA is a source based algorithm where topology control decisions are made on distributed network knowledge. The performance of TCMCA is evaluated for a static wireless network and compared against algorithms such as Connect, LINT and full power transmissions. We demonstrate that TCMCA shows better support for mission critical services for varying number of mission critical applications in the network.

I. INTRODUCTION

A mobile ad-hoc network (MANET) is a group of wireless mobile nodes working together to form a network. Such networks can exist without any fixed infrastructure and can work in an autonomous manner. Every mobile device has a maximum transmission power which determines the maximum transmission range of the device. As nodes are mobile, the link connection between two devices can break depending on the spatial orientation of the nodes. Two mobile wireless devices out of communication range can use other devices within their communication range to relay packets.

MANETs can be used to support numerous applications such as sensor networks, disaster relief, search and rescue operations including military applications where different units (soldiers and vehicles) can communicate with each other through wireless devices. Commercially, MANETs can be used in shopping malls in a city where people can message, shop or play games using their wireless devices.

The topology of a multi-hop wireless network is “a set of communication links between node pairs used explicitly or implicitly by routing mechanisms” [1]. A topology can depend

on uncontrollable factors such as node mobility, weather, interference of noise as well as controllable factors such as transmission power [1], directional antennas [2] and multi-channel communications [1].

As the transmission channel is shared, full power transmissions can reduce the network capacity by limiting spatial reuse of the channel. Lower transmission range of network nodes can decrease network robustness. For example, if the topology is too sparse then the network can become partitioned. Topology control can provide better control over network resources such that the network is well connected and applications can run efficiently.

Centralised topology control algorithms (Connect [1], Biconn-augment [1], Novel Topology Control Algorithm (NTC)[3], Global Information Full Topology (GIFT)[4], Minimum Spanning Tree (MST)[1], Relative Neighbourhood Graph (RNG) [5] and Minimum Radius Graph (minR)[5]), iteratively establish links between network nodes to achieve maximum network connectivity with minimum transmission power (in the network). Distributed topology control algorithms such as Location Information No Topology (LINT), Local Information Link-State Topology (LILT) [1], Dist-RNG [5], Dist-NTC[3] and Dis-GIF[4] maintain a certain number of neighbours or utilise the link state information of neighbours to keep the network connectivity high.

High network connectivity allows all network users to communicate with each other and reduce the chance of link failure. In order to support high priority applications in shared channel networks we may have to limit the background traffic. Connectivity based topology control algorithms mentioned in the literature do not take the application requirements and their priority when executing topology control. Hence, high priority applications running on shared channel networks may receive little satisfaction even though the network is connected [6][7][8].

In case of emergency or other critical applications, we may not need overall network connectivity but instead require reliability for some high priority services. Such mission critical applications may require a set of network devices/users to have

higher priority in the network. The network may need to disrupt other applications in order to support such mission critical services. If the network application information and user traffic load information is incorporated with topology control then we can change the topology in order to provide resources for high priority applications. The user traffic/load information can be used to evaluate end-to-end resources in a particular routing path of the network. More user traffic would lead to less end-to-end resources in a route. Thus, a topology control algorithm should use this information while making topology adaptation decisions.

This paper introduces a topology control algorithm for mission critical applications (TCMCA), which relies on a node and its link state information and the application requirements available at the source to execute topology control. Thus, mission critical applications have more chance of finding resources in the adapted topology.

Section II of this paper outlines the impact of network topology on mission critical (high priority) applications. Section III describes the proposed TCMCA algorithm. In Section IV we present our simulation results on the performance comparisons of TCMCA algorithm against a centralised topology control algorithm, such as Connect and a distributed topology control algorithm, such as LINT and a full power network topology. Section V concludes the paper.

II. TOPOLOGY CONTROL FOR MISSION CRITICAL APPLICATIONS

A. Mission critical applications

Mission critical applications refer to a set of high priority applications running in the network. For instance, in a disaster recovery situation, there can be many critical applications, such as infrastructure, communication, alert messaging, voice and data, which need to be supported by the network. The importance of tasks and services differ from time to time and region to region. For example, certain applications, like a red alert messaging service, may need to be relayed to different parts of the network. Suppose the red alert service will carry some important information and needs to be delivered within a specific time frame (application with bandwidth and delay requirements). As the channel is shared with other network nodes/users, the reliability of the red alert service will depend on the existing network topology and the traffic requirements of the network nodes. The presence of background traffic and the orientation of the network topology may imply less resources for this mission critical service. A network topology can be well connected but may not have enough resources to support such services. This is illustrated in Figure 1, in which all twenty nodes are transmitting at maximum power, resulting in a full power topology (FPT). The concentric circles in the figure represent the transmission range of individual nodes. All network nodes are well connected but lack enough resources. The lack of resources are due to the following reasons.

- Since the channel is shared, the available bandwidth can decrease rapidly with the number of contending nodes in the order of $\theta(1/\sqrt{n})$ [8][7]. Where n are the number of contending nodes in an area.

- Existing Medium Access Channel (MAC) protocols such as 802.11a, provide distributed access to the channel e.g Distributed Coordinate Function mode of 802.11a [9]. Hence, the nodes/users experience network contention [10](which introduces delay in communication in the presence of other transmitting nodes in an area).

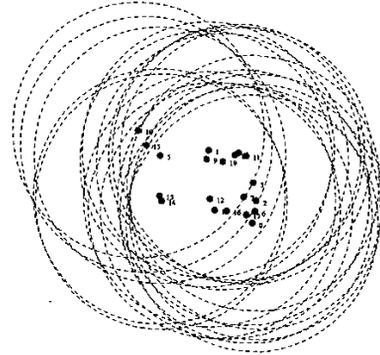


Fig. 1. A 20 node network topology with full power transmissions

Network applications consist of a series of source and destination traffic pairs which may have bandwidth, delay, jitter or throughput requirements. A network supporting such applications should satisfy these requirements. However, a network topology may only support a limited number of these applications if there are both bandwidth and delay constraints on the traffic. For example, in order to satisfy the end-to-end bandwidth requirements, we need to reduce contention by making the links less shared, but in doing so we may also increase the number of hops to the destination and thereby increase the end-to-end delay.

In ad-hoc wireless networks, we can control links by increasing or decreasing the transmission ranges of nodes. If there is an upper limit to the nodes transmission power, and nodes are static, then we have a finite number of combinations of connected network topologies. This will lead to a finite number of applications (with bandwidth and delay requirements) that can be satisfied in the network. For example, the red alert service (as discussed above) can only be satisfied if the end-to-end bandwidth requirements are made available at every hop to the destination and the delay at every hop sums up to the required end-to-end delay.

A centralised topology control algorithm such as Connect can reduce channel contention by merging the closest neighbours together by reducing their transmission ranges and making sure that the network is well connected [1]. Connect is a power optimisation approach where the algorithm tries to compute the minimum transmission ranges for nodes to keep the entire network connected. Hence, in the resultant topology, a source which had one hop to the destination when it was transmitting at full power may now experience multiple hops to the destination. Connect approach also reduces the average number of neighbours per link and thereby lowers the link contention. Such connected topology is shown in Figure 2.

LINT uses a distributed approach to reduce network contention. Each node executing LINT tries to maintain the neigh-

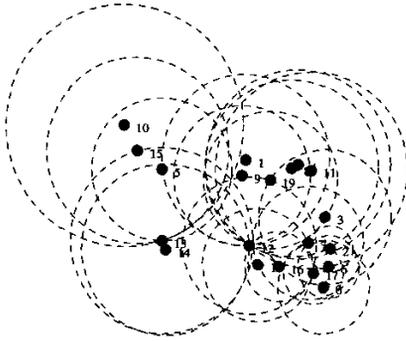


Fig. 2. A 20 node network topology after executing the Connect algorithm

hour count (node degree) to a certain value. A node increases or decreases its transmission range to add or remove neighbours. The idea behind LINT is to maintain an optimum number of neighbours per node in order to achieve high connectivity throughout the network [1].

However, LINT and Connect do not take the network's application requirements into account and therefore the resultant topology (Figure 2) is not directed to satisfy the network applications but instead is designed to reduce the overall network contention by reducing the transmission ranges of the individual nodes while maintaining network connectivity.

The minimum power approach of Connect introduces more hops to the destination so the services which require lower end-to-end delay may no longer be satisfied. Connect algorithm may also have scalability issues as all network links are established in a centralised manner which introduces large computational/processing costs, proportional to the square of number of nodes in the network [1].

LINT algorithm uses a fixed value for node degree and may result in black spots that reduce the overall connectivity of the network. Certain source destination pairs, which may have higher priority or importance in the network, may be not connected or may not have enough bandwidth/resources to support their applications.

TCMCA algorithm takes the application's delay and bandwidth requirements into account when executing topology control. Hence applications, perform better in the adapted topology.

III. TCMCA ALGORITHM

TCMCA is a source based distributed topology control algorithm which relies on it's neighbours and their link state information to compute the path from the source to the destination. Such link state information is available when using global proactive routing protocols such as Destination-Sequenced Distance Vector [11] and Wireless Routing Protocol [12].

In TCMCA, we focus on connecting the mission critical source destination pairs to satisfy high priority services in the network. Only a selected part of the network supporting such mission critical applications is connected and thus the background traffic or non mission critical traffic is restricted to the connected part of the network. We assume that the nodes are

cooperative and are willing to support topology adaptation decisions.

In TCMCA, all topology adaptation decisions are source based and one bit of state information is maintained in the intermediate nodes. This state information is used to specify whether a node is currently supporting a mission critical application.

When performing topology adaptation decisions, we take this state information into account. We do not allow any decrease in transmission power of nodes supporting other mission critical applications. If we allow this reduction in transmission power, the previous topology adaptation may experience higher end-to-end hop delay. Hence, once the topology adaptation decision is made, the other topology adaptation decisions do not increase the end-to-end hop delay of the previous mission critical source-destination pair.

The duration of such topology adaptation will depend on the duration of the mission critical application (running over this topology). If the intermediate nodes are no longer supporting any mission critical flow, the state information can be reset to the zero value.

TCMCA algorithm is executed in the following order.

- 1) **Initialisation** : During the initialisation phase every network node starts off with maximum transmission power so that the network achieves maximum connectivity. Every network node computes its one hop neighbours and stores them in a neighbour table.
- 2) **Mission-critical-connect** : Once the network is initialised the mission critical sources broadcast a topology control directive to alter the network topology. In order to reduce the network contention, the nodes lower their transmission power to the nearest neighbour, which has a route to the destination. The source nodes monitor the the end-to-end delay (in hops) and check whether the required delay is more than or equal to the existing end-to-end delay. The source node also checks whether the available end-to-end bandwidth is less than the required end-to-end bandwidth. To increase the end-to-end bandwidth and delay we decrease the transmission power of intermediate nodes in the route and introduce extra hops, which lower the contention in the route.

All topology control decisions are initiated at the source and forwarded to the intermediate nodes. If an intermediate node in the route is supporting other mission critical flows, it checks whether the new topology alteration will require this node to increase or decrease its transmission power. We only allow increase in transmission power as this will not increase the end-to-end delay requirement of the previously supported mission critical application. Otherwise, the topology control directive is forwarded to the next intermediate node in the route. This process continues till the current end-to-end delay (in hops) is less than or equal to the required delay or no other intermediate nodes are available in the route.

- 3) **Collaboration** : In order to minimise the impact of other communications on the mission critical flows a collabora-

oration directive is issued. All network nodes which are not supporting any mission critical flows then reduce their transmission power in order to minimise their impact on the mission critical applications. In our simulation we set this transmission range to zero, however, we can adjust the range to reach the nearest neighbour in case we want to maintain other communications within the network.

IV. RESULTS

A. Simulation environment

We have developed a simulation environment in C++. The simulation environment is a simple model for a wireless networks and the network characteristics are summarised as follows.

- The wireless devices use Global Positioning System (GPS) to evaluate the location co-ordinates of other nodes, however if GPS information is not available then we can use receivers signal strength to evaluate distance between two given nodes [13].
- Every node has a maximum transmission power and has an ability to vary its transmission range. The transmission power calculations are based on the first order radio model [14].
- All network links are bidirectional and we have ignored capture effects/interference that may impact the signal to noise ratio (SNR) of other network communications.
- All network nodes are randomly distributed in a grid area.
- The application requirements of the network at a given time 't' is in form of an application matrix. The mission critical applications are introduced sequentially.
- All nodes have omni-directional antennas.
- All network nodes are static.
- We assume a MAC in which the available bandwidth per hop gets divided among the contending nodes. The available bandwidth at a node is scaled down by a factor which is directly proportional to the cumulative traffic requirements of the one hop neighbouring nodes.

$$B_{i \text{ available}} = B_{i \text{ required}} * \text{scale_factor} \quad (1)$$

$$\text{scale_factor} = \frac{C}{\sum_{i=0}^N B_i} \quad (2)$$

C is the total transmission capacity of the channel and N is the number of contending flows routed through one hop neighbours. B_i is the bandwidth requirements of the i_{th} contending flow through a neighbouring node. $B_{i \text{ available}}$ and $B_{i \text{ required}}$ is the available and required bandwidth at the i_{th} node. The required bandwidth at the i_{th} node gets scaled down when the cumulative bandwidth requirements of the traffic flows in the one hop area exceed the channel capacity C .

- All traffic generated by managing the network is ignored and is left to be considered for future work.
- There is an optimised broadcast mechanism to disseminate location and application information to nodes in the network [15] [16] [17].

B. Application matrix

The application matrix is a set of source destination pairs with bandwidth and delay requirements, which can be used to state the application requirements of a network at time 't'. The structure of the application matrix used in the simulation is shown in Table 1.

TABLE I
A SET OF NETWORK APPLICATION REQUIREMENTS AT TIME (t)

No.	SRC	DEST	Band	Delay	Mission Critical
1	0	9	4	3	YES
2	1	19	2	2	NO

'SRC' represents the source and 'DEST' represents the destination identifiers respectively. 'Band' is the end-to-end bandwidth (0-11 Mbps) requirements and 'Delay' is the end-to-end delay (in hops) of an application.

C. Performance evaluation

We have simulated a 20 node 600m x 600m static network, with the maximum transmission power of 11 dBm, resulting in the maximum transmission range of 300m. We compare the available bandwidth, delay and average network connectivity for different topology adaptation algorithms against linearly increasing mission critical source and destination pairs. The results are averaged over 1000 random topologies.

Figure 3 shows a plot of the available bandwidth against increasing mission critical applications for TCMCA, Connect, LINT and FPT. Connect provides a least contention based topology to provide the maximum available bandwidth against other algorithms. Connect satisfies 75% of the mission critical applications and then starts to depreciate. The available bandwidth after executing TCMCA is greater than the required bandwidth until approximately 60% of the mission critical applications and is lower than Connect. In the case of FPT, the available bandwidth increases with the increase in mission critical traffic but only satisfies the required bandwidth until 30% of mission critical applications. In a FPT based topology, mission critical sources may experience high network contention, which can reduce the available end-to-end bandwidth.

The available bandwidth in the case of LINT increases with an increase in mission critical applications, however does not satisfy the bandwidth requirements after 30% of mission critical applications. LINT keeps the average number of neighbours to a fixed value and doesn't explicitly maintain connections between mission critical applications, therefore the topology alterations after executing LINT cannot cope with the required bandwidth. Apart from network connectivity the average contention experienced by nodes executing LINT depend on the average number of neighbours. Thus high neighbour count can increase overall network connectivity but may reduce the available bandwidth due to network contention. The average number of neighbours in LINT was adjusted to 6 to maximise the network capacity[3].

Figure 4 shows the average end-to-end delay (in hops) experienced by the TCMCA, Connect, LINT and FPT. The average

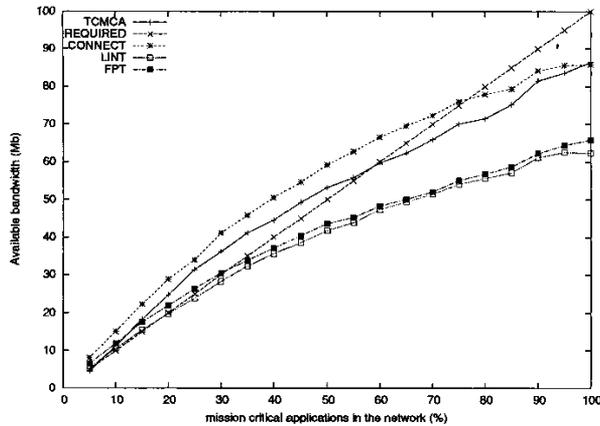


Fig. 3. Available bandwidth for mission critical applications vs % of mission critical traffic sources in a 20 node 600mx600m network

end-to-end delay in the case of FPT is minimum as all network nodes are connected with the least number of hops. On an average Connect provides a least power, highly connected network. Hence, the average end-to-end hop delay is larger than TCMCA and FPT. However, in the case of LINT, the average delay exceeds the delay of all other algorithms.

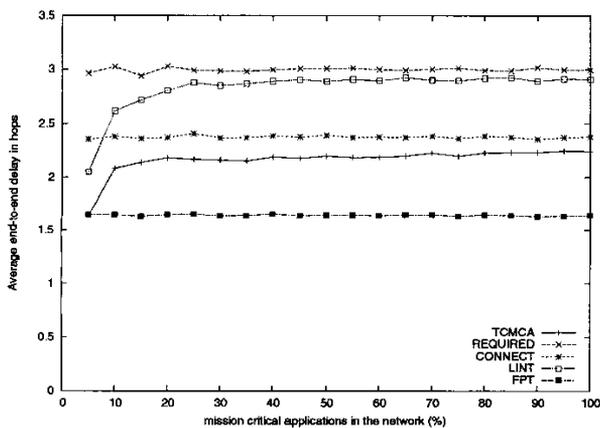


Fig. 4. Available delay for mission critical applications vs % of mission critical traffic sources in a 20 node 600mx600m network

The average end-to-end delay in case of TCMCA is '1' hop lower than the required value. This is due to the rigid model of TCMCA, where mission critical nodes are not allowed to lower their transmission power. In future, we will be looking at improving this aspect by including more flexibility in the algorithm. The required delay in the simulation varies from 2-7 hops and is quite large for a small sized network. If we reduce the delay requirements to 1-2 hops, then Connect will no longer be able to satisfy this requirement. The network size, node density and transmission ranges of nodes play an important role in determining the application performance. In future we wish to explore the dependencies of such parameters on network applications. There is a tradeoff between bandwidth and delay. In order to reduce the end-to-end delay we increase the transmission power of intermediate nodes, which in effect increases

network contention.

Connect and FPT achieve highest network connectivity as compared to LINT and TCMCA. This high connectivity of Connect was expected as it is a centralised topology control algorithm that iteratively merges all the network nodes until the entire networks gets connected. FPT is a full power topology which is always well connected. The connectivity of TCMCA increases with increase in number of mission critical source and destination pairs, thus non-mission critical traffic may suffer during mission critical communication. The overall network connectivity of LINT depends on the average number of neighbours. In our simulation LINT reaches 80% network connectivity.

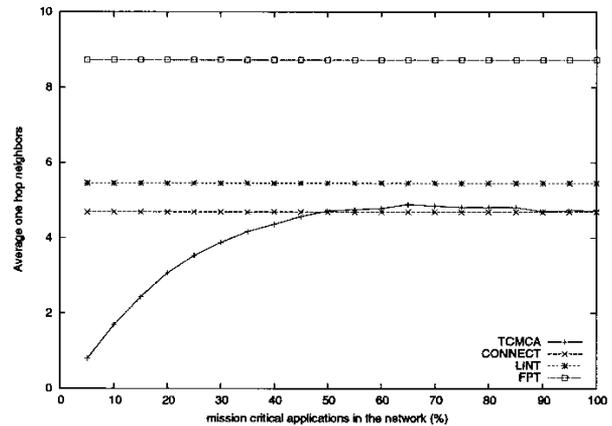


Fig. 5. Average one hop neighbours vs % of mission critical traffic sources in a 20 node 600mx600m network

Figure 5 is a plot of average one hop neighbours against increasing mission critical applications. High one hop neighbours relates to high network contention. The average neighbours in Connect is always lower than FPT as shown in Figure 5. This is expected as Connect produces the least power connected topology solution and thereby has least number of neighbours. However, TCMCA has lower neighbours on an average than Connect for the first 50% of the mission critical traffic as only selected parts of the network is connected. The average neighbour count in TCMCA increases with mission critical applications and reaches the average neighbour count of Connect. The network connectivity requirements increase with mission critical traffic, thus the average number of neighbours increase as well. The average number of neighbours in LINT are higher than Connect and TCMCA as the node degree is maintained approximately at 6. The average neighbours of TCMCA, Connect and LINT are approximately same after 50% mission critical applications, however the available bandwidth for mission critical applications is substantially higher in Connect and TCMCA.

The simulations illustrate that TCMCA achieves higher network bandwidth for mission critical applications than FPT and LINT. The available bandwidth in case of TCMCA is lower than Connect, which is a centralised topology control algorithm with computational cost of the order of $n^2 \log(n)$ [1] and needs a central node to coordinate all topology control decision, where as the TCMCA algorithm is distributed in nature. However, the simulations were done on a 20 node network. We have yet to

examine the performance of the algorithm for varying network size and densities. Such evaluations are crucial to measure the scalability of the algorithm and is left for future work.

V. CONCLUSION

In this paper we have proposed a distributed topology control algorithm to support mission critical application in a MANET. The novelty of TCMCA lies at incorporating network application requirements with topology control decisions.

TCMCA can be useful in scenarios where we want to configure the network to support a set of high priority applications and improve Quality of Service (QoS) for a set of applications in the network. In future we wish to evaluate scalability and performance of TCMCA using 802.11 MAC for large mobile ad hoc networks.

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