Delay Sensitive TDMA Slot Assignment in Ad Hoc Wireless Networks

Naresh Vattikuti, Himanshu Sindhwal, Mallesham Dasari
UURMI Systems Pvt. Ltd.
Hyderabad, India.
Email: {vvsnaresh, himanshus, malleshamd}@uurmi.com

Bheemarjuna Reddy Tamma
Department of CSE, IIT
Hyderabad, India.
Email: tbr@iith.ac.in

***Abstract*—**

Time slot assignments in a TDMA ad hoc wireless network (AWN) is either centrally coordinated by a root node or distributed among all the nodes in the network. In the centralized TDMA network, the root node uses the global knowledge of the network to assign slots, but becomes more challenging in case of distributed network, as each node is expected to assign a slot for itself without conflicting other nodes' slot selection. There is plenty of literature on how slots are assigned in a centralized TDMA network but only a few on distributed. Quality of Service (QoS) is critically important in AWNs and a good slot assignment scheme prioritizes its QoS metrics during the process of slot assignments.
Real-time communications require end-to-end delay and jitter within acceptable limits for better overall QoS. This paper proposes a delay sensitive approach to TDMA Slot assignment problem in distributed AWNs. The proposed approach does a balancing act between end-to-end delay and spatial reuse. The experimental results demonstrate that the proposed approach obtains quality results in terms of call acceptance rate, end-to-end delay and spatial reusability.

***Keywords*—TDMA Slot Assignment Scheme, End-to-End Delay, AWNs, Spatial Reuse, Call Acceptance Ratio**

I. INTRODUCTION

TDMA is a channel access method that shares the available bandwidth with multiple nodes in an energy efficient way with its slot scheduling mechanism which avoids collisions and attains better deterministic behavior when compared to contention based protocols [1].
Driven by on-field requirements and energy constraints, TDMA based channel access methods have been attracting significant interest in both military and industry sectors [2]. TDMA is widely used in radio access networks such as digital 2G cellular systems (GSM, PDC etc). It is also applied on wireless networks such as sensor networks, military, monitoring and alerting systems in the industries where end-to-end latency and bandwidth efficiency play a vital role. End-to-end delay of a flow in a multi-hop AWN scenario directly depends on the order of the slots assigned along the path. This paper proposes a slot assignment scheme which addresses the end-to-end delay while keeping bandwidth efficiency in check.
There are two main steps to be followed in order to start a communication session (i.e. flow) between two nodes in a TDMA based AWN:
1. Finding the route path from source to destination
2. Selecting and then acquiring slots at each node along the route for the flow to be set up.
In the context of this paper, we assume that the first step is taken care of by the routing module in the system [3] and in the second step, the slot selection scheme is our topic of interest.

978-1-4799-6619-6/15/$31.00

$$D_{e2e}(f) = \begin{cases} \sum_{i=1}^{N-1} ((S_{i+1} - S_i) * slotDur) \\ \qquad\qquad (\text{if } S_{i+1} > S_i)) \\ \sum_{i=1}^{N-1} ((F - S_i + S_{i+1}) * slotDur) \\ \qquad\qquad (\text{otherwise}) \end{cases} \tag{1}$$

A. End-to-End Delay

End-to-end delay is a critical QoS metric in multi-hop AWNs for real time communication. It's the total time taken for a packet to reach the destination from the source. The time taken varies based on the chosen route and the employed TDMA scheduling scheme. Each packet once received by a node, the time it waits before it is transmitted is the delay induced by TDMA scheduling at each hop. The TDMA scheduling delay is the sum of such delays at each hop. Equation-1 gives the end-to-end delay where S_i is the slot at the $'i'_{th}$ node of the N-hop ($N >= 2$) route for flow 'f'. F is the TDMA frame length and $slotDur$ is duration of each slot.

B. Spatial Reuse

Spatial reuse allows the 'TDMA Slot Assignment Scheme' to schedule concurrent transmissions for the non-interfering nodes. Opting for spatial reuse regardless of other QoS metrics can defy the quality of the communication. As an example, spatial reuse can increase the call acceptance rate in a given network. Call acceptance rate is the number of simultaneous calls supported by the network with end-to-end slot reservation in place [4].

Consider the network topology in Fig-1 and let's suppose initially frame is totally unoccupied. A 5-hop flow from Node-A to Node-F can take up to 4 TDMA frames if slots are allotted in opposite order of flow (Nodes A, B, C, D, E have been alloted slot numbers 5, 4, 3, 2, 1, respectively to support this flow). So slot selection at each node in the flow plays a major role in the flow's end-to-end delay.
In case of minimum possible delay (MPD) approach, we can always achieve minimum end-to-end delay if all the nodes on

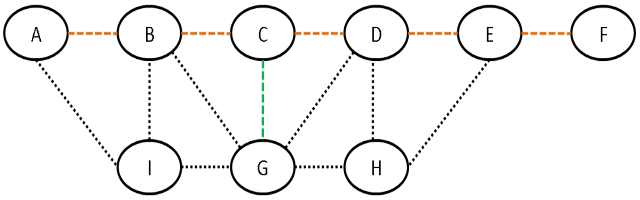

Fig. 1: Example Topology

the route from source to the destination transmit in the same sequence as that of flow like the case where nodes A,B,C,D,E assign themselves slot numbers 1, 2, 3, 4, 5, respectively, where end-to-end delay is only 4 slots. But, this slot assignment ignores the spatial reuse of slots which is vital for bandwidth efficiency and call acceptance rate. In this case, spatial reuse approach can be applied by making Node-D to use the same slot as Node-A and Node-E to use the same slot as Node-B as both pairs (A, D and B, E) are non-interfering and three-hop apart. Thereby, we have slot assignment as: A-1, B-2, C-3, D-1, E-2 in spatially reuse approach. Fig-2 depicts the two approaches.

So, at Node-D, we had two options: whether to ensure minimum delay by assigning slot-4 or ensure spatial reuse by assigning slot-1. Along with Node-A to Node-F flow, another flow from Node-G to Node-C in the topology shown in Fig-1 can lead to entirely different final slot assignments for the two approaches. If Node-A to Node-F flow had gone for MPD approach, then for Node-G the TDMA frame would appear more congested as slot-1, slot-2, slot-3, slot-4, slot-5 will appear as occupied since they are occupied by the nodes which are within 2-hop region of Node-G. On the other hand if we would have ensured spatial reuse in Node-A to Node-F flow only slot-1, slot-2, slot-3 would have appeared occupied for Node G. So MPD approach gives minimum possible end-to-end delay for the flow while other approach ensures spatial reuse but incurs more delay. The TDMA frame appears less congested in case of spatial reuse and can accommodate more flows in the network. Both the above discussed approaches have advantages and disadvantages. In this work, we try to strike a balance between the two.

The rest of the paper is organized as follows. Section-II represents work related to the current problem, Section-III outlines the proposed approach to the slot assignment problem. The experimental results are given in Section-IV. Finally, Section-V contains concluding remarks.

II. RELATED WORK

Several TDMA slot assignment algorithms for wireless networks can be found in the literature [5-9]. These algorithms can be classified into two main categories: Centralized TDMA and Distributed TDMA [5]. In centralized TDMA, a central node schedules the slots for every node in the network like a base station in a GSM network. In distributed TDMA, each node assigns a slot for itself by the underlying slot assignment scheme. Slot assignment scheme in distributed AWNs is a lot more challenging than in centralized. In this paper, we focus on distributed slot assignment in AWNs.

There exists a wide variety of literature which specifies how

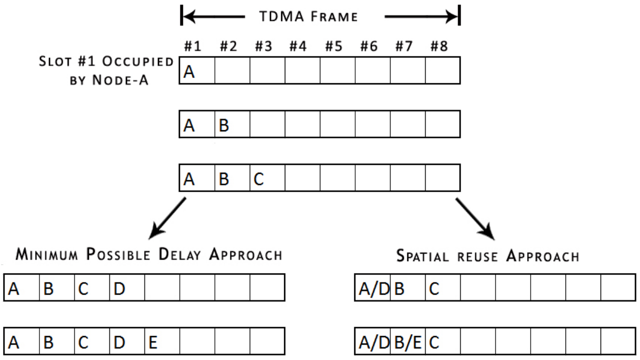

Fig. 2: Slot Assignment Approaches

QoS can be achieved in a distributed TDMA environment. In [6], spatial reuse based slot assignment scheme is proposed, which achieves higher degree of bandwidth efficiency but lacks in assuring the end-to-end delay requirements. In [7], round trip delay and spatial reusability are addressed but the slots identified as spatially reusable by its heuristic model ignores the occupied status of those slots, which makes them unusable in practical cases. In [9], delay aware TDMA scheduling is proposed where it determines end-to-end delay right after the slot assignments and ahead of the start of the data communication, but, it fails in restricting the delay to a given range. In [10], a TDMA slot assignment scheme is presented which dynamically changes the TDMA frame length to increase the channel utilization and in [4], increasing call acceptance ratio by balancing the load. But, in both the algorithms presented by Sriram et al.[4] and Kanzaki et al.[10], first available free slot is assigned to the node which induces more delay in many cases. In this paper, we made an effort to do a balancing act between meeting the end-to-end delay requirement and exploiting spatial reusability during the process of slot assignment at each node along the path of a given flow.

III. PROPOSED TDMA SLOT ASSIGNMENT SCHEME

A. System Model

The system is assumed to be well equipped with a Mobile Ad hoc Network (MANET) based routing protocol which gets the routing path for a given source and destination pair. Apart from the slot assignment scheme, the routing path attained by the routing protocol for a given flow can affect the end-to-end delay as well. But, the routing problem is beyond the scope of this paper and there exists good number of protocols such as AODV, AOMDV [3] etc in the literature [11][12][13].

It is assumed that each node transmits its and its 1-hop neighbor information in the form of beacon messages using its control slot and populates its 2-hop neighborhood information by listening to the neighbors' beacons. The 2-hop neighorhood information is critical in finding out the idle slots and slots being used by other nodes.

B. Proposed Work

The proposed work is in the context of a node which is expected to choose a slot to enable the data communication

TABLE I: Notations

Notation	Description
S_{prev}	Set of slots used by all the previous nodes in this flow
N	Number of hops the flow is spanning
F	Number of total slots in TDMA frame
$slotDur$	Slot duration in milliseconds
P	Slot used by predecessor node in the given flow. P $\in S_{prev}$
D_{max}	Max end-to-end delay acceptable for the flow
D	Maximum acceptable delay at each hop
S_{idle}	Set of idle slots in 2-hop region
$S_{selected}$	Slot chosen at current node by the algorithm
$S_{spatial}$	Set of spatially reusable idle slots in 2-hop region in the flow
S_{other}	Set of spatially non-reusable idle slots in this flow
$\Delta_{spatialmin}$	Minimum node delay among the spatially reusable slots
$S_{spatialmin}$	Slot with minimum node delay among the spatially reusable slots
Δ_{min}	Minimum node delay among the spatially non-reusable slots
S_{min}	Slot with minimum node delay among the spatially non-reusable slots

Algorithm 1 Proposed Slot Selection Scheme

```
procedure SELECTSLOT($S_{prev}$, $S_{idle}$, N, F, SLOTDUR, $D_{max}$, P)
    //If no idle slots, no further slots can be assigned
    if $S_{idle}$ = $\emptyset$ then
        return 0
    //First node in the flow picks first idle slot
    if $S_{prev}$ = $\emptyset$ then
        $S_{selected}$ = getFirstIdleSlot($S_{idle}$)
        return $S_{selected}$

    $S_{spatial}$ = IntersectionOfSets($S_{prev}$, $S_{idle}$)
    $S_{other}$ = $S_{idle}$ - $S_{spatial}$
    D = $D_{max}$ / $N$

    //Calculate delay between P and spatially available slots
    for each $S_i$ in $S_{spatial}$ do
        if $S_i > $ P then
            $\Delta_i$ = $S_i$ - $P$
        else
            $\Delta_i$ = $F$ - $P$ + $S_i$

    $\Delta_{spatialMin}$ = findMinimumofAll$\Delta_i$'S()
    $S_{spatialMin}$ = slotCorrespondingto$\Delta_{spatialMin}$()
    if ($\Delta_{spatialMin}$ * slotDur) <= D then
        $S_{selected}$ = $S_{spatialMin}$
    else
        for each $S_i$ in $S_{other}$ do
            if $S_i > $ P then
                $\Delta_i$ = $S_i$ - P
            else
                $\Delta_i$ = F - P + $S_i$

        $\Delta_{min}$ = findMinimumOfAll$\Delta_i$'S()
        $S_{min}$ = slotCorrespondingTo$\Delta_{min}$()

        if $\Delta_{min} < \Delta_{spatialMin}$ then
            $S_{selected}$ = $S_{min}$
        else
            $S_{selected}$ = $S_{spatialMin}$
    return $S_{selected}$
```

in a given flow in which the same node is a part of. The slot chosen by the node is expected to give less end-to-end delay while being conscious about spatial reuse as well. Algorithm-1 explains our proposed approach while Table-I explains different notations used in it.

If end-to-end delay for a given flow is to be within D_{max} (value set by the operator), it implies that accumulated delay at each hop should not exceed the same. Our algorithm restricts each node to select a slot such that it doesn't breach D_{max}/N (per hop-delay limit), where N is the number of hops in the flow. This restriction helps in distributing the delay constraint to all the nodes in the flow. The hop count can be fetched by using the routing protocols like AODV, AOMDV[3]. When source wants a path to destination it will send a route request for that destination. If route is found then the source node will receive a route reply containing the hop count of that path along with other details of that path. During the process of selecting a slot for itself, each node groups the idle slots in 2-hop neighborhood (S_{idle}) into two sets: spatially reusable ($S_{spatial}$) and spatially non-reusable slots (S_{other}). $S_{spatial}$ will be the intersection of the set of current idle slots (S_{idle}) on this node and set of slots used by all the nodes prior to this node (S_{prev}) in the current flow. S_{other} will contain the remaining slots in S_{idle} which are not there in $S_{spatial}$. Then for each slot in $S_{spatial}$, a delay (Δ_i)will be calculated which will be the delay incurred on this node if that slot is chosen. Basically this delay will be the time difference between P (slot used by the predecessor node in the flow) and the slot in $S_{spatial}$ set. Once delay for all the slots in $S_{spatial}$ is calculated we will find a slot which gave minimum delay and call it $S_{spatialMin}$ and the corresponding delay as $\Delta_{spatialMin}$. If this slot is inducing a delay less than D (=D_{max}/N) then this slot will be selected and the algorithm completes else we will move to set S_{other} and repeat the process to find the slot in S_{other} which will give minimum delay among all the slots in S_{other}, we will call it S_{min} and the corresponding delay as Δ_{min}. If Δ_{min} < $\Delta_{spatialMin}$ then we will select the slot S_{min} (the idle slot giving minimum possible delay on this node) otherwise $S_{spatialMin}$ (the idle slot giving minimum possible delay on this node and also spatially reused in the flow) will be chosen. The summarization of the whole approach is that a node selects a spatially reusable slot closer to the slot used by the previous node in the flow if the chosen slot is inducing a delay within per hop delay limit (D). If none of the spatially

TABLE II: Values used in Simulation

Parameter	**Value**
Number of Nodes	20
Number of Slots	32
Slot duration	1ms
Number of Seeds	15
Average $Dmax$	200ms
Transmission Range	1.5units
Area	20x20units

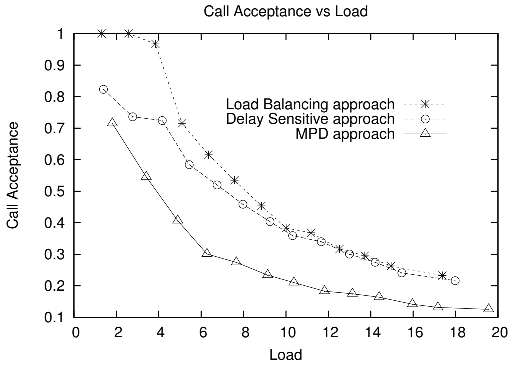

Fig. 3: Call Acceptance vs Load (Random Topology)

reusable slots are satisfying this criteria then node selects a slot which will induce minimum delay among all the available idle slots irrespective of the fact whether it is giving spatial reuse or not. It should be noted that the proposed algorithm is a slot selection algorithm which will choose a slot. Once slot is chosen, node will not start using it right away instead it undergoes a typical 3-way handshaking procedure like in [10] for acquiring the chosen slot in which node will request the slot, gets replies from its neighbors and finally send the final decision whether it is acquiring the slot or not. So there might be a case where two (or more) adjacent nodes (nodes within 2-hop neighborhood)end up choosing same slot after running our proposed algorithm but only one of them will be able to acquire that after 3-way handshake and slot will be collision free, other nodes will choose a different slot again using the proposed algorithm. Also this 3-way handshake slot acquisition process can introduce significant random delay at each hop of the flow but that will happen only during bandwidth reservation phase in which every node in the flow is acquiring a slot for that particular flow. Once slots are reserved along the path at each hop the data packets of the flow will not suffer any random delay and only significant delay that will come into picture is the time during which a node is waiting for its transmission slot to arrive for sending the packet.

IV. EXPERIMENTAL RESULTS

In this section, we use the simulator developed in [4], as our objective is to calculate the end-to-end delay in a multi-hop network and call acceptance ratio with respect to varying load ($Average flow arrival rate \times Average flow duration$). For carrying out the experiments, we arranged the nodes in string topology as well as connected random topologies. The parameters used in the topology are given in Table-II. The setup consists maximum of 20 nodes with a transmission range of 1.5 units (1.5×200 meters) each, with an equal interference range.

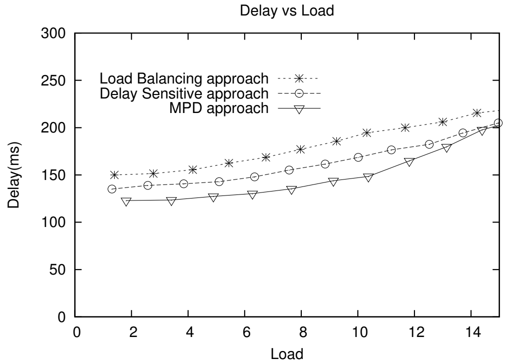

Fig. 4: Delay vs Load (Random Topology)

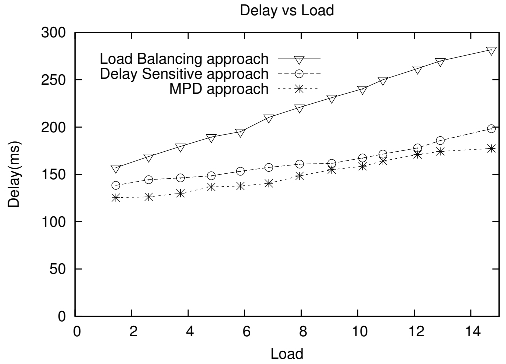

Fig. 5: Delay vs Load (String Topology)

We have analyzed three types of experimental results, one being end-to-end delay with varying load, second is the call acceptance ratio with varying load and the last is call acceptance ratio with different values of D_{max} by keeping the load fixed.The simulation is run for several seeds with dynamically changing the source destination pairs of flows in the network at runtime.

We have compared the call acceptance ratio and delay of 'Load Balancing' approach[4], MPD approach and our work (Delay Sensitive Approach) with varying load. We have also compared the delay with respect to varying number of hops, as our algorithm performs better for long hop flows. 'Delay Sensitive' approach curve lies between the 'Load balancing' approach and MPD approach displaying the tradeoff between the other two. The curve of 'Delay Sensitive' approach in Fig-3 shows that, it achieves greater call acceptance ratio than MPD approach, because of spatial reusability. And also, the 'Delay Sensitive' approach's curve in Fig-4 shows that the delay with the increased load is as good as MPD approach and outperforms 'Load Balancing' approach. Furthermore, the curves in Fig-5 and Fig-6 show that our approach giving better results in case of flows with more hop count as the probability of tradeoff between delay and spatial reuse happens more frequently. In Fig-7, the 'Delay Sensitive' curve shows that

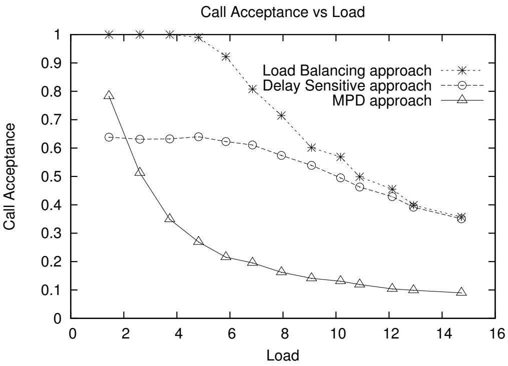

Fig. 6: Call Acceptance vs Load (String Topology)

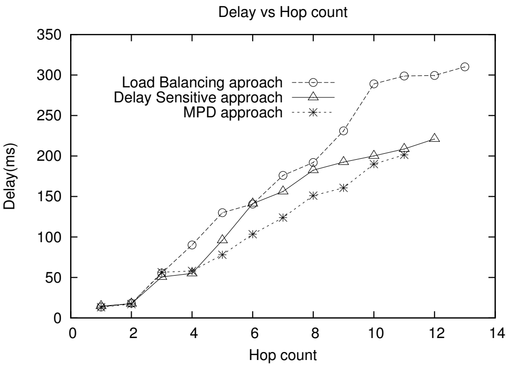

Fig. 7: Delay vs Hops (String Topology)

delay accumulated is reduced as the hop count increases and is closer to MPD approach.

Additionally, we calculated the call acceptance with varying the D_{max} value as shown in Fig-8. The curve shows that, the Delay Sensitive approach gives more call acceptance with the increased D_{max}, as the increase in D_{max} lead to increase in maximum delay at each hop which will further enhance the spatial reuse.

V. CONCLUSIONS & FUTURE WORK

In this paper, an end-to-end delay sensitive approach is provided for slot selection by exploiting the spatial reusability in multihop AWNs. The results show that the developed algorithm balances well between the delay and spatial reusability metrics. It is also shown from the results that, it performs well for long hop flows.

The tradeoff between the two metrics proposed in this paper can be expanded to other QoS metrics in distributed TDMA slot assignment process. Prioritizing among different QoS metrics helps in finding a better tradeoff.

REFERENCES

[1] De Rango, F.; Perrotta, A.; Ombres, S., "A energy evaluation of E-TDMA vs IEEE 802.11 in wireless ad hoc networks," Performance Evaluation of Computer and Telecommunication Systems (SPECTS), 2010 International Symposium on , vol., no., pp.273,279, 11-14 July 2010

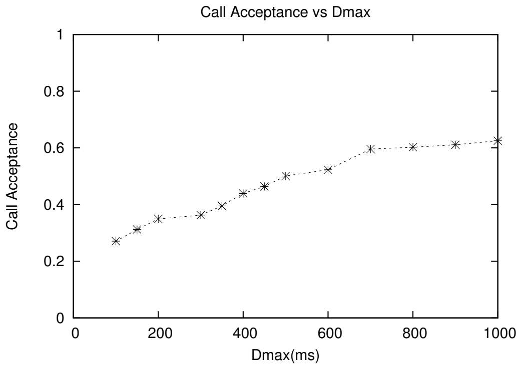

Fig. 8: Call Acceptance vs D_{max} (String Topology)

[2] Braten, L.E.; Voldhaug, J.E.; Ovsthus, K., "Medium access for a military narrowband wireless ad-hoc network; requirements and initial approaches," Military Communications Conference, 2008. MILCOM 2008. IEEE , vol., no., pp.1,7, 16-19 Nov. 2008

[3] Yuhua Yuan; Huimin Chen; Min Jia, "An Optimized Ad-hoc On-demand Multipath Distance Vector(AOMDV) Routing Protocol," Communications, 2005 Asia-Pacific Conference on , vol., no., pp.569,573, 5-5 Oct. 2005

[4] Sriram, S.; Reddy, T.B.; Manoj, B.S.; Murthy, C.S.R., "The influence of QoS routing on the achievable capacity in TDMA-based ad hoc wireless networks," Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE , vol.5, no., pp.2909,2913 Vol.5, 29 Nov.-3 Dec. 2004

[5] Young, C.D., "USAP multiple access: dynamic resource allocation for mobile multihop multichannel wireless networking," Military Communications Conference Proceedings, 1999. MILCOM 1999. IEEE , vol.1, no., pp.271,275 vol.1, 1999

[6] Gore, A.D.; Karandikar, A.; Jagabathula, S., "On High Spatial Reuse Link Scheduling in STDMA Wireless Ad Hoc Networks," Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE , vol., no., pp.736,741, 26-30 Nov. 2007

[7] Djukic, P.; Valaee, S., "Link Scheduling for Minimum Delay in Spatial Re-Use TDMA," INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE , vol., no., pp.28,36, 6-12 May 2007

[8] Chaudhary, M.H.; Scheers, B., "Progressive Decentralized TDMA Based MAC: Joint Optimization of Slot Allocation and Frame Lengths," Military Communications Conference, MILCOM 2013 - 2013 IEEE , vol., no., pp.181,187, 18-20 Nov. 2013

[9] Djukic, P.; Valaee, S., "Delay Aware Link Scheduling for Multi-Hop TDMA Wireless Networks," Networking, IEEE/ACM Transactions on , vol.17, no.3, pp.870,883, June 2009

[10] Kanzaki, A.; Uemukai, T.; Hara, T.; Nishio, S., "Dynamic TDMA slot assignment in ad hoc networks," Advanced Information Networking and Applications, 2003. AINA 2003. 17th International Conference on , vol., no., pp.330,335, 27-29 March 2003

[11] Xun-bing Wang; Zhan Yong-Zhao; Wang Liang-Min; Li-ping Jiang, "Ant Colony Optimization and Ad-hoc On-demand Multipath Distance Vector (AOMDV) Based Routing Protocol," Natural Computation, 2008. ICNC '08. Fourth International Conference on , vol.7, no., pp.589,593, 18-20 Oct. 2008

[12] Xu Zhen; Yang Wenzhong, "Bandwidth-aware routing for TDMA-based mobile ad hoc networks," Information Networking (ICOIN), 2013 International Conference on , vol., no., pp.637,642, 28-30 Jan. 2013

[13] Perkins. C. E and Royer. E. M, "Adhoc On-demand Distance Vector Routing", Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA99. Second IEEE Workshop, pp. 90-100, 1999