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Cross-layer Architecture Resource Accessibility through cross-layer control in Mobile Ad-hoc Networks

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ABSTRACT

The different layers of the network interface with each other for information transfer. In the cross-layer architecture the physical layer and medium access layer share information so that these information becomes available to the higher layers. The power control information of the physical layer and channel allocation information of the medium access layer are shared are shared with the upper network layers. Interference is a big challenge in wireless networks, so the communication links between two nodes use bit rate as the function parameter in the physical and access layer. The channel and network topologies vary from milliseconds to several seconds depending on the connection variation. The network control mechanism finds out the access control vector and the traffic forwarding decision to accomplish the quantitative performance objectives. The network performance objectives are overall throughput, power optimization and utility optimization of allocated resource rates. The cross-layer control algorithms with optimal performance are presented and analyzed. In this paper the detailed analysis and design techniques are presented.

I. Introduction

In the cross-layer design architecture, the physical layer and the medium access layers parameters are shared with the routing layer and transport layer. Due to the dynamic nature of wireless nodes, the channel and network topologies these features are captured through a control vector. The information that is available in different layers is to be considered based on nature of the variability in order to obtain the optimum performance. The topology state variable is being taken to represent all the environment parameters that affect the communication process. The network control mechanism needs to find the access control vector and traffic forwarding decision to provide optimum or suboptimal performance. Capacity region is the parameter that attributes to the network performance. The capacity region considers the long term average communication topology and the traffic load matrices. One capacity region of a network must be different from another capacity region of a specific policy. Hence the network capacity is the accumulation of all the individual capacity regions taken over all possible control policies. The network performance is better if it has a larger capacity region. Hence, the network performance will move towards stability for wider range of traffic loads and robust to traffic variations. This network performance stands to be very important for wireless ad-hoc network as the network capacity and traffic load are always changing due to dynamic nature of the network. One of the important policies that optimize other performance objectives is the max weight adaptive back pressure policy. This policy is an essential feature to optimize the other performance objectives. The selection of the various control parameters from the physical layer to transport layer is performed in two steps in max weight adaptive back pressure policy. All the factors that affect the transmission rates of the wireless links are selected in the first step. In the second step all the flow control decisions and routing decisions to control multi-hop traffic forwarding are determined. The back pressure policy consists in giving priority to the traffic classes having higher backlog differential. The transmission rate of a link that leads to highly congested regions of the network is throttled down. In this way the congestion notification travels backwards all the way to the source and flow control is performed.

II. Related Works

A. Goldsmith, et al. [1] in his paper discussed about the channel quality and desired rates by selecting different modulation constellation. The channel quality depends on the different modulation techniques available in the medium access layer.

M.J. Neely, et al. [2] in their paper discussed that due to huge interference in the multi-node wireless communication, the communication links between pairs nodes of nodes can be viewed as independent but also as an interacting entities where the bit rate of one is a function of choices for the physical and access layer parameters of the others.

M.J. Neely, et al. [3] in another paper discussed that the topology state and channel is very dynamic. The topology state may not be fully available to the network access controller but may only observe only a sufficient statistics of that. The communication topology is a function of state topology and control vector that represents the physical and medium access layer variables.

A. L. Stolyar [4] discusses that the link rate is also dependent on the signal-to-Interference plus noise ratio. The packets are generated by any node and that the traffic flows from the source to the destination according to the network and transport layer protocols.

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L. Tassiulas, et al. [5] in their paper discussed that the traffic forwarding types may be datagram, multicast traffic or virtual circuits as well.

A. Eryilmaz, et al. [6] in their work focused that resource allocation can be fairly done by maintaining queues in the network layer and transport layer. By maintaining the stability of the queue length there can be fair resource scheduling and also congestion control.

M. Andrews, et al. [7] in their paper discussed those possibilities of providing quality of services on the wireless communication by sharing information among the network layers. Through cross-layering the control access is possible when the energy level of the signals and channel allocation of the access layer are communicated to the network layers for routing.

M. Chiang, et al. [8] discussed in their paper that there is a need for balancing transport layer information with the physical layer. The end-to-end delivery of information will match well with flow control of traffic when there is a balance in the power level, scheduling and delivery of traffic.

III. Network Models and operational Assumptions

A. Networks Models

A network model is considered that comprises a set of mobile nodes (N) and transmission links (L). The network topology evolves according to an irreducible Markov chain with finite state pace S and time average probabilities π_s for $s \in$ S. The transmission links represent a communication channel between the nodes and it is labeled as (a, b) where (a, b) ε N There may or may not be direct communication the nodes. The link capacity and transmission rate keep varying due to node interference, node mobility, weather conditions etc. If there is no direct communication between two nodes then transmission rate of links (a, b) is zero else L is a strict subset of all ordered pairs of nodes. The network is assumed to operate in slotted time with slots normalized to integral units, t ε {0,1,2,3……}and each slot refers to time interval (t, t+1). If $U_{Tr}(t)$ represent the transmission rate matrix over link (a, b) during time slot t.

$U_{Tr}(t) = U_{Tr\,(a,b)}\,(t)$ if there is a link over (a, b).

$U_{Tr}(t) = 0$ for all time t when there is no physical link between a and b.

The link transmission rates $\mu(t)$ are determined by link transmission rate function C (I, S).

$$\mu(t) = C\,(I(t), S(t)) \qquad (1)$$

The function $C\,(I(t), S(t))$ illustrates the physical layer and medium access layer properties of the network. The abstract function view of the network helps to provide an understanding of the basic control techniques to all data network and enables to take maximum advantage of the unique features of the data link layer.

I(t) represents link control input of all possible resource allocation choices under the topology state S(t). It specifies the group of links chosen for activation during t timeslot, bandwidth allocation decisions for every data links, bandwidth allocation decisions for every data link, the matrix of power values allocated for transmission over each data link. I(t) is control decision variable with a topology state-dependent control space $I_{S(t)}$.

S(t) represents all the uncontrollable parameters of the network due to user mobility, weather conditions, wireless fading that causes interference and channel conditions to change time to time. It also includes current set of node locations and current attenuation coefficients between each node pair. S(t) contains huge amount of information but for simplicity of modeling it is assumed that, it takes finite state space S and it remains constant for the duration of timeslot t.

The network controller observes the current topology state S(t) and selects the transmission control input I(t), where I(t) ε $I_S(t)$ and $I_S(t)$ is the general state space following some transmission control policy. The function C(I, S) is a matrix valued and is composed of individual $\mu_{ab}(I, S)$ functions that specify individual transmission rates on each link (a, b) so that $\mu_{ab}(t) = C_{ab}(I(t), S(t))$.

Distributed implementation is difficult as rate function for a single link can depend on the full control input I(t) and full topology state S(t). This is often facilitated when rate functions for individual links depend only on the local control actions and the local topology state information associated with those links. The transmission rate function C(I(t), S(t)) describes the properties of the physical layer and medium access layer of a given network. C(I(t), S(t)) = C_{ab}(I(t), S(t)) where C_{ab}(I(t), S(t)) is the transmission rate over link (a,b) constraint under control action I(t) and state topology S(t) for (a, b $\in$ { 1,2,…N}).

B. Properties of Mobile ad-hoc network

A mobile ad-hoc network comprises of set of N mobile nodes as shown in fig.1. The location of each mobile user is quantized to a rectilinear cell partitioning that covers the network region of interest. The cell location of a node a during time slot t is represented as $S_a(t)$ and topology state variable is comprised of the vector $(S_a(t))_{a\,\varepsilon\,N}$ that means one component for node and changes from slot to slot as the nodes moves from one cell to cell. The nodes move according to some mobility process that is different from node to node. The transmission rate function I(t) of link L can be given by SINR model where the signal attenuation coefficient are determined by the current node locations. The transmission rate function for link L is given by $C_L(I(t), S(t)) = C_L(P(t), S(t))$ and this function depends on the signal to interference plus noise ratio (SINR) according to logarithmic capacity curve.

$$C_L\,(P(t), S(t)) = \log(\,1 + SINR_L(P(t), S(t))) \qquad (2)$$

$$\text{Where } SINR_L\,(P(t), S(t)) = \frac{P_L\,(t)\,\alpha_u(S(t))}{N_0 + \sum_{\substack{k\,\varepsilon\,\mathcal{L}\\ k \neq L}} P_k(t)\,\alpha_{kL}(S(t))} \qquad (3)$$

P_L (t) denotes the power that the transmitter of link l allocates for transmission so let P(t) represent the power allocation vector hence $P(t) = (P_{L\,(t)})$ so control input is equal to P(t).

$\alpha_{kL}(S(t))$ represents attenuation coefficient factor at the receiver link L of the signal power transmitted by the transmitter of link k while the topology state is S(t)

N_0 represents the background noise intensity on each link.

The mobility mode is not specified so any mobility model like Markovian random walk, periodic walks, independent cell hopping, random waypoint mobility, etc can be used. The network model does not considers inter-cell interference and assumes that nodes can transmit to other nodes in the same cell and adjacent cells and at most one node can transmit in a cell in a single timeslot.

$I_{ab}(t)$ represents the control process that takes value 1 is link (a,b) is activated during time slot t and zero otherwise. $I_{ab}(t)$ represents the matrix of transmission decisions restricted to control space I_{ab} that specifies the feasible link activations in the topology S(t).

It is assumed that transmission rate within a cell is assumed to be h packets/slot and of an adjacent cell transmission is L packets/slot (where h ≥ L).

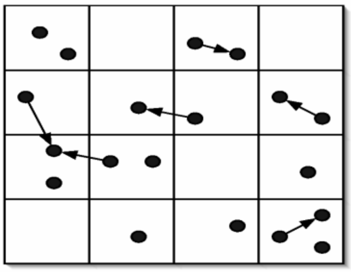

Fig. 1. Cell partitioned structure of mobile ad-hoc network

The link transmission rate function is given by
C_{ab} (I(t), S(t))= $C_{ab}(I_{ab}(t), S_a(t), S_b(t))$
and C_{ab}(I,S) takes units of packets/slot._

$$C_{ab}(I_{ab}(t), S_a(t), S_b(t)) = \begin{cases} h \text{ if } I_{ab}(t) = 1 \text{ and } S_a(t) = S_b(t) \\ 1 \text{ if } I_{ab}(t) = 1 \text{ and } S_a(t) \neq S_b(t) \\ 0 \text{ else} \end{cases}$$

Where ($I_{ab}(t)$ ε $I_{s(t)}$) This network model allows a single node to transmit over one frequency band and receiving over another frequency band. This couples transmission decision over the entire network and complicates optimal distributed control.
For obtaining sub-optimal scheduling some approaches are:

- Allow nodes to send transmission request and allow an arbitrator process to determine the request grant. In this the arbitrator process may run several times to improve scheduling decision. One-step arbitration method is used in 802.11 and multi-step arbitration is used in packet switches.
- Another approach is to select a set of transmitter nodes and receiver nodes in every time slot and only the nodes in the sender set are valid receiver nodes.

The control techniques used in this paper is done by considering the desired performance targets and the current network conditions.

C. Network Operational Assumptions

In this section the different modes of operations that are assumed are discussed. Time slot assumption: Time slots are used to represent periods corresponding to new channel conditions and control actions. This assumption presumes synchronous operation where control actions in the network take place according to a common time clock. The timeslot is assumed to be short in comparison to the slow fading and non predictable fast fading the timeslot is assumed to be short in comparison to slow fading and long in comparison to fast fading.

ii) Channel measurement:

The network components have the ability to monitor the channel quality in the form of specific set of attenuation coefficients or channel classifications such as “good”, “medium”, “bad”. Channel measurement technology is currently implemented for cellular communication with High Data Rate services. For satellite communications with long round trip times, channel measurement can be combined with channel prediction.

iii) Error-free transmission

In this work, it is assumed that all data transmissions are successful with significantly high probability. If transmission errors are rare, the extra arrival rate due to such error is small and do not appreciably change network performance. This type of error is neglected and treats all transmission as error-free.

IV. Network layer- Queuing

The input “c” that enters the network consists of the source node identifier, destination node identifier, data and priority service class. Inputs “$A_i^{(c)}(t)$” enter the network layer in terms of bits or units of packets and it is generated by the user of source node i. Every traffic generated do not enter the network layer but the transport layer in node i defines “$R_i^{(c)}(t)$” as the amount of input permitted to enter the network layer. Each node “i” maintains a set of internal infinite buffer storage space queues for storing network layer data according to its input. The set of input in the network are represented by “k”. The unfinished work “$U_i^{(c)}(t)$” is stored in the network layer, it stores both the inputs that arrived through the transport layer and through the network layer from other nodes. The network layer control algorithm makes decisions about scheduling, resource allocation and routing based on the current topology state and queue backlog information. The primary aim is to ensure all the queues be stable so that time average backlog is finite.
The controller at each node a ε N selects the routing decision variable “$U_{ab}^{(c)}(t)$” subject to the following routing condition

$$\sum_{c\in K} U_{ab}^{(c)}(t) \leq U_{ab}^{(c)}(t) \qquad (4)$$

$$\mu_{ab}^{(c)}(t) = 0, \text{ if } (a,b) \notin L_c$$

$U_i^{(c)}(t)$ denotes the current backlog of input c data stored in the network layer queue in node i, it may be both the data that arrived from the transport layer at node i and data that arrived through the network layer transmissions from other nodes. Routing restriction is defined for each attribute, so L_c is the set of links (a,b) which c is allowed to use.

The resource allocation decision $I(t) \in I_{s(t)}$) determines the transmission rates $\mu_{ab}^{(c)}(t) = C_{ab}$ (I(t), S(t)) over the link (a,b) in timeslot t.

IV. Transport layer- flow control

The transport layer stores all the incoming input “$A_i^{(c)}(t)$” in a storage reservoir before forwarding it to the network layer. It is assumed that separate storage reservoirs exist for each input and the backlog “$L_i^{(c)}(t)$” of the input c bits is stored at each node i in the transport layer. The storage reservoirs may be finite or infinite with size $0 \leq L_i^{max} \leq \infty$. The source node i makes flow control decision by selecting the amount of bits “$R_i^{(c)}(t)$” to be sent to the network layer at node i subject to the flow control constraint

$$R_i^{(c)}(t) \leq L_i^{(c)}(t) + A_i^{(c)}(t) \text{ for all (i, c) and t} \qquad (5)$$

V. Back Pressure and Resource Allocation Algorithm

The algorithm is designed for the network as discussed in section III. The network has irreducible Markov chain with finite state space S process. The dynamic back pressure and resource allocation algorithm is considered for a multi-hop network, where input c is associated with link (a,b) traffic, so L_c= {(a,b)}. It is also assumed that the backlog queue “U(t)” at the destination node is zero.

The network controller performs routing and resource allocation by observing the backlog queue and topology state variable S(t) every time slot t.

A. Resource allocation algorithm:

1. Begin
2. Newly arrived traffic from the user enters the transport layer.
3. It is stored in the transport layer storage reservoir (n,c) and forwards the regulated traffic $R_a^{(c)}(t)$ to the network layer.
   The network layer stores it in the internal queues.
   Select routing control action I(t)

4.1 Observe current topology state

4.2 Select I(t) ∈ $I_s(t)$ to obtain maximum link transmission rate $\mu(t) = C(I(t), S(t))$.

5. End

B. Scheduling algorithm:

1. Begin
2. Take up a link (a,b) and an input c,

2.1 choose $\mu_{ab}^{(c)}(t)$ to satisfy the following constraints:

$$\sum_{c \in K} \mu_{ab}^{(c)}(t) \leq \mu_{ab}^{(c)}(t) \qquad (6)$$

$$\mu_{ab}^{(c)}(t) = 0, \text{ if } (a,b) \notin L_c$$

where L_c is the set of all network links that are acceptable for input c data to traverse

End

VI. Proposed Cross –layer Control algorithm

The approach to through the cross-layer control tries to ensure stability of the network and the utility is suboptimal. A source-input pair (n,c) is considered to be an active session where (n,c) Є D and $g_n^{(c)}(r)$ are not identically zero. The active sessions (n,c) have infinite backlog in their corresponding reservoirs such that flow variables $R_a^{(c)}(t)$ may be selected without first establishing that this much data is available for admission. The above assumptions are made to highlight the fundamental issues of resource allocation, flow control and routing.

A. *Algorithm for routing and scheduling:*

1. Begin
2. Every node n observes the backlog in all neighboring nodes j connected by outgoing links (n, j).

$$W_n^{(c)}(t) = U_n^{(c)}(t) - U_j^{(c)}(t) \qquad (7)$$

stands for the differential backlog of input c and define

$W_n^{(c)}(t) \triangleq \max_{lc} \mid l \in L_{cj} \{ W_{nj}^{(c)}(t), 0 \}$, here, $L_{cj}(t)$ is for maximum input and data of input $c_{nj}^*(t)$ is selected for (potential) routing over link (n,j) whenever $W_{nj}^*(t) > 0$.

3. End

B. *Algorithm for resource allocation:*

1. Begin
2. The current topology is observed to take transmission decision I(t) Є $I_{s(t)}$
3. A transmission decision is taken by maximizing

$$\sum_{n,i} W_{ni}^*(t)\, \mu_{ni}(t) \qquad (8)$$

where $\mu_{ni}(t) = C_{ni}(I(t), S(t))$, the resulting transmission rate of $\mu_{ni}(t)$ is offered to input $C_{ni}(t)$ data on link (n,j). Null bits are padded in case any node does not have enough bits of a particular input c and send on all the outgoing links.

4. Is (no-of-bits sufficient for a particular input C)
5. If Yes, then send it on all outgoing links
6. Else pad null bits on the bit to make it a complete load to be sent out on all outgoing links from the node.
7. End

C. Algorithm for flow control

1. Begin
2. The flow controller at each node observes the current status of the queue backlog queue $U_n^{c(t)}(t)$, every timeslot for each input c Є {1,….K}.
3. It then sets $R_n^{(c)}(t) = r_n^{(c)}(t)$, where $r_n^{(c)}(t)$, are the values selected according to the optimization

Maximize:

$$\sum_{c=1}^{k} \left\lfloor V g_n^{(c)}(r_n^{(c)}) - r_n^{(c)} U_n^{(c)}(t) \right\rfloor, \qquad (9)$$

Subject to

$(r_n^{(c)}) \geq 0$, $\sum_{c=1}^{k} r_n^{(c)} \leq R_n^{max}$, V>0 is a chosen constant that affect performance of the algorithm.

4. End

VII. Results and Discussions:

VIII. Conclusion

The cross-layer resource allocation algorithm using back pressure approach discussed in this text is modeled for usages in different areas of wireless communication. The different load balancing and routing problems studied by the theoretical Computer science community falls within the scope of the proposed model here. The different policies proposed in that context rely on the differential backlog rule for traffic forwarding. The scheduling policies are based on tolerable complexities, centralized or distributed applications and this is dependent on the different applications. One approach to deal with high scheduling complexity is to resort to randomized scheduling policies. In these polices a randomized algorithm computes the access schedule at each time and it updates the one used previously only if it is better. The randomized algorithm being of low computational complexity simplifies the computational requirements, without sacrificing any throughput but only with some increase of the delay. When the network is geographically distributed, collecting state information for the access controller might be cumbersome and might result in outdated information available to the controller.

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