An Optimization Framework for IEEE 802.11s Based Wireless Mesh Network

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Abstract— Wireless mesh network (WMN) is a promising area of research. Energy efficiency in WMN can play vital role in achieving green wireless communication. This research work considers IEEE 802.11s link based power saving modes. Energy aware joint optimization of routing, link scheduling under wireless interference and delay constraint has been considered. For given traffic load a model has been formulated to minimize network energy consumption by choosing optimum power saving mode for peer links. It is stressed that redundant links and nodes can be turned in low power state for energy savings.

Keywords- *Energy saving; IEEE 802.11s; Link based power saving mode; Wireless Mesh Network; Redundant links;*

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I. INTRODUCTION

With rising access to digital mobile devices, internet is contributing a vital function in daily life. Since last decade internet users and mobile users has increased globally. This has directed towards technology extension in wireless network. This necessity has nourished acceleration for progress in wireless mesh network (WMN) to provide access to Internet via gateway nodes. Request from client nodes are directed to gateway nodes in multi hop means and inversely. IEEE 802.11s is a standard [1] developed to support WMN. In contrast to previous IEEE 802.11 standards, each mesh node in IEEE 802.11s based network can maintain power saving mode (PSM) for each peer link independently of others. Standard supports three PSM i.e. active, light and deep. Each node has its own target beacon transmission time (TBTT). For active mode towards a link, a node can start transmission anytime as need arise. While, in light mode a node wake up at TBTT of peer nodes and wait to receive any data from peer node. Deep sleep mode is most energy conservative. Here a node doesn't need to listen to TBTT of peer nodes and can stay in sleep mode for longer durations. By opting deep sleep state for redundant peer links energy saving can be enhanced significantly. But IEEE 802.11s doesn't gives PSM switch criteria. The PSM of link can be established as per network fix demand, remaining battery capacity, quality of service (QoS), traffic to support etc.

Networks are designed to meet QoS for peak traffic conditions. But network resources are not utilized up to their full capacity during low traffic periods. In scenario of traffic following a pattern on periodical basis [2], the resources can be dynamically adjusted according to current traffic level. Keeping this in view problem of optimum PSM for peer links based on given traffic load has been formulated in this research work.

The main contributions of the paper are summarized as follows:-

(1) In scenarios when network traffic follows a pattern on periodical basis, a detailed modeling for optimal PSM for peer links has been given.
(2) Problem of energy minimization under various constraints has been considered.
(3) A Mathematical Programming Language (AMPL) has been used to solve the proposed model.

The remaining of text is organized as follows. Section II describes related area of work. Section III gives the model for optimization problem under various constraints to achieve optimal PSM for links. Section IV gives simulation. Finally, concluding remarks and future direction are presented in section V.

II. RELATED WORKS

There is extensive research in field of wireless sensor, ad hoc, mobile network etc. But yet energy saving aspects of WMN is not fully explored. Moety et al. [3] allows switching off selected base station and adjusting the power level of remaining active nodes. Optimization problem has been designed for an access based network and solution can't be applied to select optimal PSM for a link. Chang et al. [4] reduces the energy consumption of network by load balancing. The network life time is prolonged by deciding routing path based on left over energy of each node, location of sink node and transmission distance. Badawy et al. [5] addresses the problem of assigning resources in a solar based WMN for optimal selection of battery and solar panel sizes for each network node. To maximize network life time the precedent solar radiation and bandwidth usage is utilized. Hou et al. [6] proposed time slot scheduling subject to link capacity. Projected solution reduces energy consumption by reducing link ideal state, bandwidth wastage, energy consumption due to link scheduling. None of mentioned work targets link scheduling along with routing. Energy due to switching of state of node and exchange of control packets has been completely ignored. Keeping this in view energy aware joint optimization of routing, link scheduling under flow, interference and delay constraint has been formulated in this paper. To the best of our knowledge this is first work which addresses optimal selection of PSM for peer links to switch off redundant nodes.

III. PROBLEM FORMULATION THROUGH OPTIMIZATION FRAMEWORK

Network is represented in graphic notation as MN(L,M,G,A,T) where L is set of directed links as in (1), M is set of 'r' mesh router, G is set of $'g'$ gateways, and $A = \{a_i\}$ is a set of $'a'$ mesh access points (MAP). An MAP accumulates traffic from its client's nodes and forwards the request to gateway nodes via router nodes in multi hop fashion. $T = \{t_i\}$ is a set of traffic demands with delay bound D_{max} .

$$L = \{l_{i,j}\}\ i = 1 \dots N,\ j = 1 \dots N \qquad (1)$$

Where, $N = r + g + a$

$l_{i,j} = 1 \Rightarrow$ Link exist between node i and j

$l_{i,j} = 0 \Rightarrow$ Link doesn't exist between node i and j

Denoting active, deep sleep and light sleep mode towards peer node j as $n^a_{i,j,m}$, $n^d_{i,j,m}$, $n^l_{i,j,m}$ respectively.

$$A_{i,m} = n^a_{i,1,m} \text{ or } n^a_{i,2,m} \text{ or } n^a_{i,3,m} \text{ or} \dots n^a_{i,k_i,m} \qquad (2)$$

$$L_{i,m} = n^l_{i,1,m} \text{ or } n^l_{i,2,m} \text{ or } n^l_{i,3,m} \text{ or} \dots n^l_{i,k_i,m} \qquad (3)$$

$$D_{i,m} = n^d_{i,1,m} \text{ or } n^d_{i,2,m} \text{ or } n^d_{i,3,m} \text{ or} \dots n^d_{i,k_i,m} \qquad (4)$$

$$n^d_{i,1,m} = \\ \text{not}[\left(n^a_{i,1,1} \text{ or } n^a_{i,2,1} \text{ or } n^a_{i,3,1} \text{ or} \dots n^a_{i,k_i,1}\right) \text{or} \dots \text{or}\left(n^a_{i,1,S} \text{ or } n^a_{i,2,S} \text{ or } n^a_{i,3,S} \text{ or} \dots n^a_{i,k_i,S}\right) \text{ or} \\ \left(n^a_{1,i,1} \text{ or } n^a_{2,i,1} \text{ or } n^a_{3,i,1} \text{ or} \dots n^a_{k_i,i,1}\right) \text{or} \dots \text{or}\left(n^a_{1,i,S} \text{ or } n^a_{2,i,S} \text{ or } n^a_{3,i,S} \text{ or} \dots n^a_{k_i,i,S}\right) \\ ] \qquad (5)$$

Equations (2), (3), (4) are Boolean OR over peer links states of a node.

Result $A_{i,m} = 1$ implies existence of a peer active link with node i in slot m

Result $L_{i,m} = 1$ implies existence of a peer light sleep link with node i in slot m

Result $D_{i,m} = 1$ implies existence of a peer deep sleep link with node i in slot m

Equation (5) allows peer links of node in deep sleep mode if duration of doze state is long enough of frame duration i.e. if node is not transmitting or receiving in any of m slot. Node can go in doze state but wake up only to transmit its own beacon.

IEEE 802.11s draft standard implements both contentions based and an optional contention free access. Later is mesh coordination function controlled channel access (MCCA) by allowing mesh routers to negotiate collision-free transmission reservation schedule, called MCCAOPs, in a hop-by-hop manner exchanged in control part. MCCAOP specifies the beginning of the first MCCAOP and duration of the MCCAOPs i.e. slot duration in multiples of 32 µs. When, frame is delivery traffic indication map (DTIM) interval with typical value of 32 ms/102.4 ms, there are 1000/3200 possible time slots (6).

$$S = \frac{\text{Framesize}}{\text{Slotduration}} \qquad (6)$$

WMN are designed to link to exterior network. Different to third layer routing of existing standards, WMN architecture is more appropriate for second layer routing. Thus, IEEE 802.11s supports routing protocol at layer two. Joint optimization of routing and link scheduling can lead to better energy performance. Problem of slot allocation is NP hard. With demand of guaranteed QoS in multi hop network and energy conservation, it is preferable to schedule links so that minimum energy state of network can be achieved under desired QoS. Considering IEEE 802.11s contention free access where transmission over link is divided into slots of fixed duration. Let control traffic is being carried over separate channel and doesn't interfere with ongoing data transmission. IEEE 802.11s doesn't specify the duration, schedule and condition of switching mode. Under single data channel, objectives are to choose path or allocate slots for given demands under QoS constraint to allow and lengthen PSM of nodes and links. Towards objective of minimizing energy consumption of whole network (7), energy aware joint optimization of routing, link scheduling under flow, interference and delay constraint has been considered. Optimization approach can be compared with the concept of Resource Consolidation (RC) [7] which is an approach to achieve energy efficient objective by consolidating the network traffic on a selected set of active network nodes and shutting down other lightly loaded nodes.

As minimum granularity of sleep state can be a slot. A node i with k_i peer nodes, a link $l_{i,j}$ can be in any of PSM during a slot $'m'$ i.e. active, deep sleep and light sleep mode towards peer node j. Active state signifies whether a slot k is reserved for link $l_{i,j}$. Peer links acting in active mode participate in data transmission/reception. But a light sleep node must wake up to transmit or receive peer beacons. Let a node can go in doze state if duration of light sleep state is long enough for frame duration. IEEE 802.11s lacks specification for power change mode logic. Link based power mode should be chosen carefully, else may result in poor quality of service.

Definition:- Beacon matrix $BT_{n*n*S} = \{b_{i,j,m}\}\ 1 \le i \le N, 1 \le j \le N, 1 \le m \le S$ is a matrix with dimensions given by number of nodes and number of time slots in a frame of a graph MN. Value of any element in matrix $b_{i,j,m}$ identifies if TBTT has been scheduled.

Where, $b_{i,j,m} = 1$, if TBTT of node i is scheduled in slot m and $l_{i,j} = 1$ and j is peer node to listen TBTT of i.

$b_{i,j,m} = 0$, if TBTT of node i is scheduled in slot m and $l_{i,j} = 1$ and j is not peer node of i.

$b_{i,j,m} = 0$, if TBTT of node i is not scheduled in slot m

A. *Objective function formation*

According to IEEE 802.11s standard for power saving a mesh node may choose to enter in doze state i.e. can set the transceivers off only if the mesh node operates in light sleep mode or deep sleep mode for all of its mesh peering. For maximum gain all of peer nodes should be in light/deep sleep state under given delay constraints. A node acts in active mode while transmitting or receiving over link $l_{i,j}$ or $l_{j,i}$ in m^th slot. Total energy consumption in network can be computed as below.

$$E_{total} = \sum_{i=1}^{n} \sum_{j=1}^{k_i} \sum_{m=1}^{S} E_{i,j,m} \quad (7)$$

Where, $E_{i,j,m} = U + V + W + X + Y + Z$

TABLE I. SUMMARY OF NOTATIONS

Notation	Definition
E_{LA}	Switch energy
E_d	Static energy per second
S	Number of slots per frame
B	Bandwidth
$T_{i,j}$	Energy consumption to transmit a packet from node i to j
$R_{j,i}$	Energy consumption to receive a packet at node j from node i
t^s	Traffic per slot that can be transmitted
D_{awk}	Duration of awake window
E_b^T	Energy consumption for transmitting a beacon
E_b^R	Energy consumption for receiving a beacon
k_i	Number of peer links of node i
R_{awk}	Ideal energy consumption, while waiting for receiving peer beacon

U is energy consumed due to switching state (8), transmitting or receiving nodes will wake up if not already in active state for exchange of beacons. Switching energy can be minimized if network nodes are allocated continuous slots for data communication. Term $E_{LA} * n_{i,j,m}^a * \left(1 - A_{i,m-1}\right)$ signifies a node needs to switch whenever current state of slot is 1 and there was no active link in its previous slot. While, term $E_{LA} * \left(1 - A_{i,m-1}\right) * b_{i,j,m}$ indicates node will wake up to transmit beacons of its own, and there was no active link in its previous slot. Similarly term $E_{LA} * \left(1 - A_{i,m-1}\right) * (\sum_{j=1..n} b_{j,i,m}) * (1 - n_{i,j,m}^a)$ *(1-$n_{i,j,m}^d$) stands for receiving beacons from peer nodes.

$$U = E_{LA} * n_{i,j,m}^a * \left(1 - A_{i,m-1}\right) + E_{LA} * \left(1 - A_{i,m-1}\right) * b_{i,j,m} * (1 - n_{i,j,m}^a) + E_{LA} * \left(1 - A_{i,m-1}\right) * (\sum_{j=1..n} b_{j,i,m}) * (1 -$$
ni,j,ma) *(1-ni,j,md)
(8)

V is static energy (9). W is energy consumed in transmitting data (10). X is energy consumed in receiving data (11). Y is energy consumed in transmitting beacon (12). Z is energy consumed in receiving beacons (13), energy consumption for receiving peer beacons in deep sleep state is zero.

$$V = n_{i,j,m}^a * E_d * \text{slotduration} + \left(E_d * \frac{S}{B}\right) * b_{i,j,m} * (1 - n_{i,j,m}^a) + E_d * R_{awk} * b_{j,i,m} * (1 - n_{i,j,m}^a) * (1 - n_{i,j,m}^d) \quad (9)$$

$$W = T_{i,j} * t^s * n_{i,j,m}^a \quad (10)$$

(11)

$$X = R_{j,i} * t^s * n_{i,j,m}^a$$

$$Y = \left(D_{awk} + E_b^T\right) * b_{i,j,m} * n_{i,j,m}^a + E_b^T * b_{i,j,m} * (1 - n_{i,j,m}^a) \quad (12)$$

$$Z = E_b^R * b_{j,i,m} * (1 - n_{i,j,m}^d) \quad (13)$$

B. Constraints Formation

For a link between nodes i and j i.e. if $l_{i,j} = 1$, then $n_{i,j,m}^a + n_{i,j,m}^d + n_{i,j,m}^l = 1$ ensure that a link in slot m can be in at most one power save state. Whereas $n_{i,j,m}^a + n_{i,j,m}^d + n_{i,j,m}^l = 0$ implies $l_{i,j} = 0$.

$$n_{i,j,m}^a + n_{i,j,m}^d + n_{i,j,m}^l = l_{i,j} \quad (14)$$

Where $n_{i,j,m}^a, n_{i,j,m}^d, n_{i,j,m}^l \in (0,1)$

A given network must satisfy flow conservation rule. Equation (15) ensures routing path is discovered at each node. Where, t^s is traffic handled per slot. Only conflicts between active links need to be considered. Active link is defined as link with not null flow scheduled. For communication over single channel Equation (16), (17), (18) and (19) ensures law of wireless communication as in fig 1. Equation (16) make certain that at a node i for a given slot is active in only one peer link, allocation of slots at multiple peer links is avoided hence maintains the law of communication as in fig. 1(A) i.e. a node can't transmit to more than one destination simultaneously. Equation (17) assures that a node i don't receive from two nodes simultaneously, a node can't receive data flows from more than one source fig. 1(B). Equation (18) Fulfills each node can't receive and transmit simultaneously fig. 1(C). Equation (19) Ensures Transmitter-Receiver-Transmitter Conflict i.e. two sources can't transmit at the same time while the transmitter and the receiver share a neighbor which can hear both transmissions in fig. 1(D).

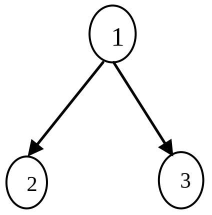
$$\sum_{m=1}^{k} n_{i,j,m}^a - \sum_{m=1}^{k} n_{j,i,m}^a = \begin{cases} \frac{t_i}{t^S} & \text{if } i = \text{Source} \\ -\frac{t_i}{t^S} & \text{if } j = \text{Destination} \\ 0 \text{ if } i \neq \text{Source and } j \neq \text{Destination} \end{cases} \quad (15)$$

$$n_{i,j,m}^a - \sum_{p=1,p!=j}^{k_i} n_{i,p,m}^a = 1 \; \forall \; i = 1 \ldots N, j = 1 \ldots k_i, m = 1 \ldots S \quad (16)$$

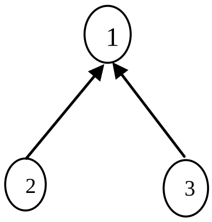
$$n_{j,i,m}^a - \sum_{p=1,p!=j}^{k_i} n_{p,i,m}^a = 1 \; \forall \; i = 1 \ldots N, j = 1 \ldots k_i, m = 1 \ldots S \quad (17)$$

$$n_{i,j,m}^a - \sum_{p=1,p!=j}^{k_i} n_{p,i,m}^a = 1 \; \forall \; i = 1 \ldots N, j = 1 \ldots k_i, m = 1 \ldots S \quad (18)$$

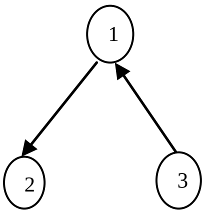
$$n_{i,j,m}^a - \sum_{p=1,p!=j}^{k_i} n_{l,p,m}^a = 1 \; \forall \; l \in \text{peer}(p) \; i = 1 \ldots N; \; j,l = 1 \ldots k_i; m = 1 \ldots S \quad (19)$$



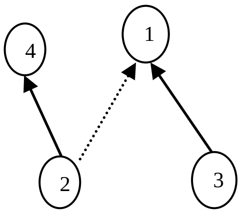
(A) Transmitter-Transmitter conflict



(B) Receiver-Receiver conflict



(C) Transmitter-Receiver conflict



(D) Transmitter-Receiver-Transmitter Conflict

Figure 1. Wireless Communication Conflicts over a Single Channel

In wireless network delay of a packet can be due to processing, queuing, transmission, propagation and interference delay. Processing delay (order of micro seconds) is due to time taken in processing header part of a packet. This can play significant role when complex encryption algorithm or packet content examined. Processing delay followed by queuing delay, which is waiting time in queue. Transmission delay D^T as in (20) is actual time taken in pushing bits of a packet on link which depends on size of packet and link rate. Propagation delay D^P (21) is time taken in travelling the first bit from sender to receiver node over physical medium given by distance between nodes and speed of link for wireless medium i.e. by speed of light. Interference delay play vital role in wireless communication. For TDMA protocol interference delay is determined by delay due to scheduling of link D^S as in (22). Delay due to scheduling of link D^S is specific to slot allocation. Traffic at a MAP follows path P consisting of link set $L = \{l_{ij}\}$. The routing path and link state must meet delay bound constraints D_{max}.

$$D^T = \frac{\text{Size of Packet}}{\text{Bandwidth}} * t_{i,j} \qquad (20)$$

$$D^P_{i,j} = \frac{\text{Distance Between Node (i,j)}}{\text{Speed of Light}} \qquad (21)$$

$$D^S_{i,j} = \frac{\sum_{j=1}^{k} m}{\text{No of slots per Frame}} \quad \forall n^a_{i,j,m} = 1, m = 1 \qquad (22)$$

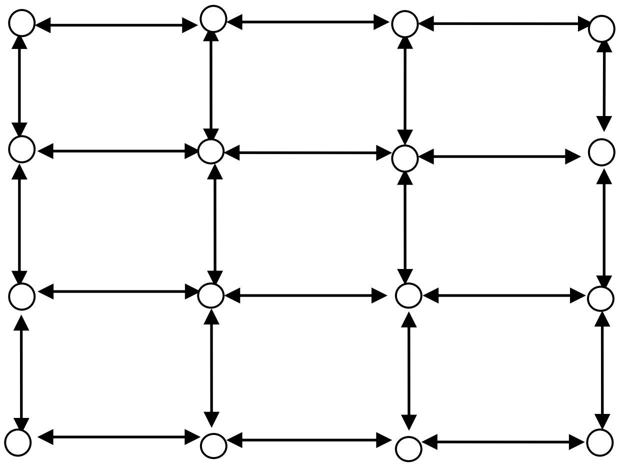
$$\sum_{(i,j)\in P} l_{i,j} * \left(D^T + D^P_{i,j}\right) \le D_{max} \qquad (23)$$

Considering transmission and propagation delay, constraint (23) ensures traffic is routed within acceptable delay bounds due to transmission and propagation delay. Optimization problem becomes minimization of equation (7) under given constraints (14) and (15-19, 23).

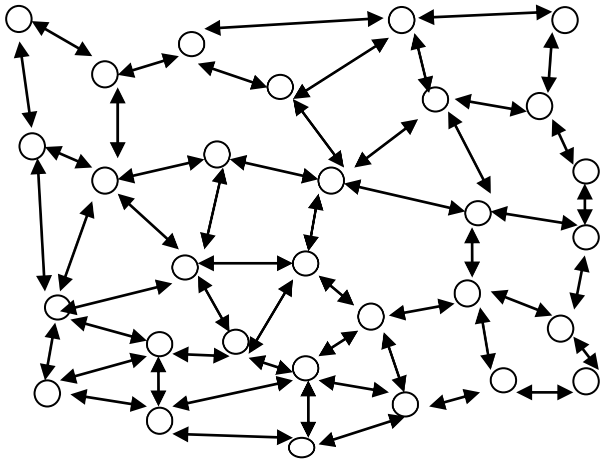
With network size number of variables increases exponentially. Solving the optimization problem can be computational very expensive and practically not feasible [8]. To reduce the complexity of our non-linear optimization problem, the non-linear terms has been converted to its linear equivalent to reduce the optimization problem into a Boolean Linear Programming.

IV. SIMULATION

Problems have been solved in AMPL. Grid topology of 16 nodes and random topology with 30 nodes has been considered as in fig. 2(A) and fig. 2(B) respectively. In each topology 3 MAP and 1 gateway node are chosen randomly. Average results of ten random instances for both are given in table 2. Parameters as Beacon Interval = 102.4 ms , Slot duration = 32 µs. Number of slots =3200 Bandwidth = 54Mbps, Data rate=1Mbps, Delay constraint=110 ms or 50 ms, Beacon size =162 bytes, Packet size = 216 bytes, Beacon interval =102.4ms and from table II has been considered. Further, each slot can transmit 1 packet under assumed parameters. Data rate of 1Mbps implies ~ 580 packets per second or 60 packets per beacons. It is found that, significant energy can be saved by opting power saving mode, which further increase as delay constraint is relaxed.



(A)



(B)

Figure 2. (A) Grid Topology (B) Random Topology

TABLE II. RESULTS OF OPTIMUM PROBLEM

Type of Analysis \ **Scenarios**		**Delay 110ms**		**Delay 50ms**	
		Case I GRID Topology	**Case II Random Topology**	**Case I GRID Topology**	**Case II Random Topology**
Energy Consumption without power saving mode and in null traffic (J)		11.85	22.23	11.85	22.23
Energy Consumption with power saving mode and in null traffic (J)		0.24	0.47	0.24	0.47
Optimum Energy Consumption with power saving mode in traffic	Minimum (J)	8.02	11.78	8.89	12.14
	Average (J)	8.72	12.98	9.12	13.29
	Maximum (J)	9.10	13.87	9.54	14.67

V. CONCULUSION AND FUTURE WORK

This work represents importance of wireless mesh network in today network. Energy efficiency aspects of IEEE 802.11s have been sketched. Moreover, according to IEEE 802.11s standard a mesh node may choose to enter in doze state (in doze state a mesh node may set the transceivers off) for power saving only if the mesh node operates in light sleep mode or deep sleep mode for all of its mesh peering. A detailed model for optimum PSM for peer links subject to delay constraint has been proposed. By reducing redundant peer links energy saving can be enhanced in 802.11s. Analysis reveals that optimum PSM of peer links can achieve great energy efficiency. But solving the optimization problem can be computationally expensive. An approximation algorithm will be proposed for minimum energy consumption in next research work.

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