Enhanced Energy Saving Mechanism for Multi-Radio Multi-Channel Wireless Mesh Networks

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Abstract—**Multi-radio multi-channel (MRMC) mesh networks improve latency and spectrum utilisation, but at the cost of increased energy consumption. The standard mesh networking power saving mechanism (802.11 PSM) does not apply to MRMC. We propose an enhanced energy saving mechanism, EESM, in which each node switches its radios between different energy states based on observed traffic. In an empirical evaluation, we investigate the tradeoff between energy savings and decreased goodput. We show that energy savings are possible without impacting goodput, and that more aggressive control can generate more significant energy savings.**

I. INTRODUCTION

With the increase in Internet of Things deployment and the move to 5G networks, the interest in multi-hop wireless mesh networking is growing (e.g. [4], [10], [15]). WMNs are also emerging as low cost access networks for developing countries (e.g. [5], [7]). A WMN consists of multiple nodes connected in a graph topology, including clients, routers and internet gateways. Nodes can communicate peer-to-peer, using multi-hop paths through the network, with acceptable latency for delay-tolerant or low volume traffic. For higher traffic demands, if the radios are restricted to a single channel, or nodes have only a single radio, then congestion can occur and latency increases.

MRMC mesh networks use multiple radios on each node, with radios able to use different channels. This reduces interference between nodes, and allows a node to handle multiple flows simultaneously, thus reducing latency and increasing throughput. However, this introduces an additional energy cost in order to support the multiple radios.

Various power saving mechanisms for WMNs have been proposed and implemented. However a power saving mechanism for a MRMC WMN is still an open problem. In this paper we have proposed an enhanced energy saving mechanism (EESM) for such networks. EESM tries to put the maximum number of radios to sleep mode while maintaining the network efficiency. The proposed technique is compared in terms of energy consumption, delay and goodput with a network using no energy saving mechanism and conventional power saving mode. Experimental evaluation shows that EESM can save significant energy over the default power saving mode (PSM), without degrading network performance for both constant bit rate flows and HTTP traffic, for low and medium traffic loads.

II. RELATED WORK

Different approaches have been proposed to reduce energy consumption in single radio WMNs. IEEE 802.11 provides a power-saving mechanism for distributed coordination function (DCF) based single radio mesh WLANs. The basic idea of PSM is to put radios to sleep mode whenever they are in idle state for long periods. A radio in sleep mode consume less energy as compared to when in idle state. By putting more radios into sleep mode whenever feasible, a network can save some energy. PSM divides the time into identical beacon intervals which remains fixed with each interval comprising of a small ad hoc traffic indication map (ATIM) beacon exchange interval and larger data exchange interval. In each ATIM beacon exchange interval, radio on each node switches to a default channel to exchange ATIM beacons. Nodes which want to communicate with another exchange these beacons and then exchange data in data interval. Rest of the nodes which are not actively communicating switch their radios to sleep mode and stay asleep for the interval. The duration of this ATIM beacon exchange interval has great importance as a very small period would not be sufficient enough to receive all ATIM beacons causing delays and a very large period would not be very energy efficient. PSM is the standard approach for saving power but does not cater for MRMC. Basic implementation of PSM over MRMC WMN only considers state of a node putting all its radios in same mode or controls each radio individually as a single entity. Both approaches fail to take full advantage of having multiple radios per node for energy saving. Nodes end up keeping more radios awake even in a case where less radios could do the same job.

[1] proposed an adaptive ATIM beacon exchange interval for PSM but nodes need to propagate these changes among each other and still require tight time synchronization. Energy aware routing assigns routes on the basis of total energy consumption per route or remaining energy in battery operated nodes (e.g. [11], [12]). They have discussed energy efficient routing but did not consider the capability of nodes or radios

to sleep for saving overall energy. One proposal is to adapt the transmission power of the radios while satisfying throughput needs [3]. Having multiple radios operating on different power levels on same node are prone to self interference and shadowing etc. ([2], [6]) have reviewed common energy efficient protocols for network and data link layer respectively, and [8] has discussed energy saving protocols at routing layer for WMNs.

The available literature mainly focuses on single radio WMNs and only a few papers considered MRMC WMNs. [14] proposed an adapted PSM technique for MRMC networks. In their approach, nodes should maintain a table for their neighbouring nodes and respective common channels. One of the radios per each node switches to a default common channel in every ATIM exchange period. In ATIM exchange period, nodes which want to communicate with each other negotiate the channel and radio over common channel and then exchange data in data interval over negotiated link. Radios which are not involved in communication over this period are put into sleep mode.This scheme is applicable to MRMC networks where each radio is assigned a fixed channel and each radio acts as independent transceiver. In this method, a node can communicate with at most R number of neighbours in one interval where R is the number of radios on that node. Nodes will have less chances to put radios into sleep mode with higher number of traffic flows in the network.

III. ENHANCED ENERGY SAVING MECHANISM (EESM)

EESM aims to take advantage of having multiple radios per node for energy saving. Nodes divide radios into receivers and transmitters. Receivers are assigned channels in fixed manner, the transmitters switch dynamically to the channels over which they can communicate to respective nodes. A single radio can transmit up to N number of neighbours where N is the number of available channels. In general more number of channels are available than the number of radios per node $N \geq R$. This allows less number of radios to communicate with more number of nodes thus permitting more radios to go to sleep in contrast to standard PSM [14].

Lets consider a mesh topology with M nodes and N orthogonal channels, where each node is equipped with R number of radios. Each node classifies one radio as a receiver R_r and others as transmitters R_t. Channels are assigned to receiver radios using game theoretic approach given in [9]. Each node stores a table for neighbouring nodes with their respective receiving channel. When there are multiple flows J going through a node, a virtual queue Q_j for each flow is maintained and assigned to a corresponding neighbour/channel. Node assigns active channels to the transmitter radios uniformly.

Buffer capacity of a node is L and queue occupancy of a node is given by

$$Q_{occupancy} = \sum_{j=1}^{J} Q_j \tag{1}$$

$$Q_{occupancy} < L \tag{2}$$

Time is divided into equal intervals T_{int} and within each interval a transmitter radio switches to respective channels for communicating with assigned neighbours accordingly. Different scheduling mechanisms can be used for switching transmitter channels. A simple fixed round robin scheme is explained below.

A. Fixed Round Robin Scheduling

From J flows, node assigns a list of n neighbours to a transmitter. Transmitter radio remains on receiving channel of first neighbour in n for a fixed time of T_{ch}, then switches to the receiving channel for the next neighbour in list n and so on. If there is only one neighbour assigned to a transmitter then during each T_{int} the transmitter will stay on the same channel and will not require switching. If more than one neighbour is being assigned to the transmitter then it will switch between n channels in each T_{int} for equal time T_{ch}.

$$T_{ch} = \frac{T_{int}}{n} \tag{3}$$

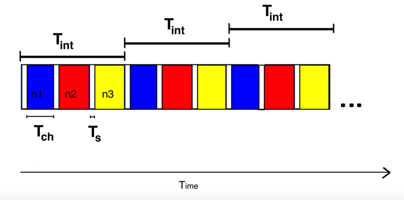

Fig. 1. Fixed Switching Schedule for a Transmitter Radio Over 3 Channels

Figure 1. shows an example where a transmitter radio has been assigned three active queues which have packets to transmit. Transmitter keeps switching between three channels and each interval is distributed evenly between queues. For more than one active queues per transmitter, each queue has to wait for time T_{del} before its served again.

$$T_{del} = (n-1)T_{ch} + nT_s \tag{4}$$

T_s is a very small switching delay which incurs for every channel switch and can be calculated as

$$T_s = t_{cs}(f - f') \tag{5}$$

t_{cs} is a fixed switching unit and depends on the hardware of radio card, f and f' are frequencies of previous and new channels respectively. T_s is very small and negligible. T_{del} should be kept under a threshold level to avoid long delays at radios. A threshold value depends on type of traffic and its delay sensitivity. A smaller value allows radio switching only if resulting additional delays are very small for current flows. Larger value on the other hand put radios into sleep mode more often and results in higher queueing delays.

$$T_{del} \leq T_{th} \tag{6}$$

TABLE I
PARAMETER NOTATIONS AND VALUES FOR EXPERIMENTS

Parameter	Notation	Value for Exp.
Number of nodes	M	16
Number of channels	N	11
Radios per node	R	3
Buffer size of a node	L	255 pkts
Transmitter radios per node	R_t	2
Receiver radios per node	R_r	1
Active flows per node	J	1-10
Active queues per transmitter	n	1-11
Time interval for one cycle	T_{int}	0.1s
Delay threshold	T_{th}	65,75,80 ms

B. Objective

A radio can be turned ON or OFF at a node and a node can further switch the states of ON radio between awake or asleep mode. ON radio which is taking part in transmission or reception is in active state and consumes highest energy. ON radio which is not participating in any active communication is in idle state. When a radio is idle it is consuming less energy than active state and can switch to active state by itself whenever there is a demand to transmit or receive. In sleep mode, radio consumes the least energy but can not take part in any communication.

Each node defines a variable X_i to maintain the state of radio i on it.

$$X_i = \begin{Bmatrix} 0 & awake \\ 1 & asleep \end{Bmatrix} \tag{7}$$

The objective, as per below equation, is to save energy, while satisfying Eq(6).

$$Max \sum_{i=1}^{R} X_i \tag{8}$$

C. State Transition

The state switching decision for a radio is made at each node in a distributed manner.

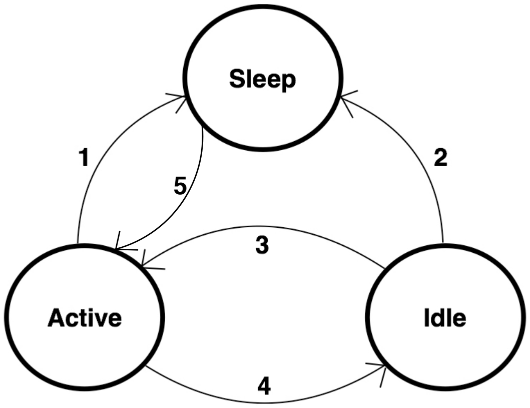

Fig. 2. State Diagram of a Radio Interface

1) Active → Sleep: If by putting radio into sleep mode, constraint Eq(6) is not violated, the node will assign the active queues on that radio to another awake radio and put it into sleeping mode.
2) Idle → Sleep: If a radio has been idle for a time period t, then the node will switch it to sleep mode. No active queues should be assigned to it as long as it is sleeping.
3) Idle → Active: If there are packets in any assigned queue for a radio it will start transmitting.
4) Active → Idle: If all assigned queues are empty for a radio, it will go to idle state.
5) Sleep → Active: If Buffer is full ($Q_{occupancy} = L$) causing incoming packets to drop or T_{del} is exceeding the (T_{th}) with sleeping radios available then one or more sleeping radios are put back into active mode and assigned some active queues.This will make queueing delay smaller for each flow emptying buffer in a faster manner avoiding packet drops.

Each node maintains a table for its neighbours and their respective receiver channels. It also stores a transmitter table keeping information about channels assigned and current states of each transmitter. Each node can independently make a decision of switching states of transmitters and then transmitter table is updated accordingly. It is to be noted that this information is required on the node locally and does not effect the route of the flow. Each node tries to use least number of interfaces while satisfying the traffic demand and keeps other interfaces in sleep mode hence minimizing energy consumption.

IV. RESULTS AND ANALYSIS

A number of experiments were carried out to evaluate EESM. A grid topology mesh network comprising of 16 nodes each equipped with three radios is simulated using network simulator ns3. A set of 11 orthogonal channels is available and channel assignment scheme [9] is used to minimize co-channel interference. Performance of EESM is compared with PSM and a network without any energy saving (WES) mechanism. The values and parameters used in experiments are given in Table I and II [13]. An extensive search was carried out to find suitable values for T_{th}.

TABLE II
ENERGY PARAMETER VALUES

Energy Parameters	Value
Supply Voltage V	3 V
Idle Current of a radio I_{idle}	0.313 A
Transmitting Current of a radio I_{tr}	0.79 A
Receiving Current of a radio I_r	0.367 A
Switching Current of a radio I_s	0.0167 A
Sleeping Current of a radio I_{sleep}	0.096 A

Total running time for simulation is hundred seconds. Two different types of traffic flows are used. In first case ten constant bit rates (CBR) flows for peer-to-peer traffic are used. In second case ten HTTP flows are generated with mixed peer-to-peer and gateway oriented traffic. CBR (UDP) flows are benchmark to evaluate the simulations and HTTP (TCP) flows reflect real traffic. Each experiment was run ten times with different seeds for generating random flows while keeping duration and load constant per flow. Performance is measured in terms of energy, delay and goodput. Energy efficiency is measured by dividing total energy consumed by sum of successful transmissions in the network. This gives energy used per successful bit transmission. A network having lower value for this metric is more energy efficient. Packet Delay is end-to-end delay a packet faced from source to destination over each flow. Goodput is calculated using successfully received packets in transmission duration for each flow.

A. *CBR Traffic using UDP*

In first set of experiments, ten CBR flows are generated using udp client and server in peer-to-peer fashion. Packet size is 1460 bytes, packet interval is 0.01s and, bandwidth is set to 1Mbps.

Figure 3 shows the mean values of energy consumed per node and energy efficiency of network for each scheme. Figure 4 gives the comparison for network performance parameters which are mean packet delay for a flow from source to destination and mean goodput across a flow.

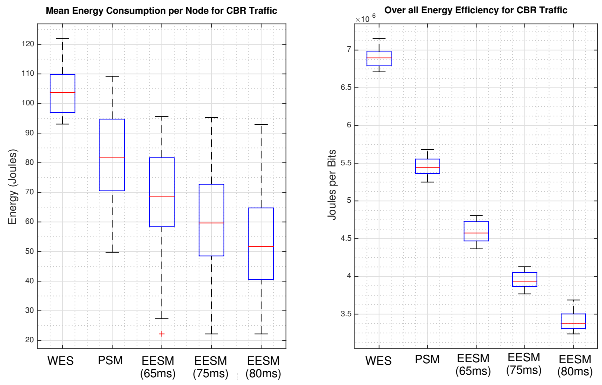

Fig. 3. Comparison of Mean Energy Consumption per Node and Over all Energy Efficiency of CBR Traffic

WES is a mesh topology without using any energy saving mechanism and as expected, consumes the highest energy per node. PSM uses less energy compared to WES while keeping mean packet delay and goodput for each flow equivalent with WES. For EESM, three different sets of simulations were conducted to analyze the impact of different values of T_{th}. With higher values of T_{th}, nodes tend to put radios into sleep mode more aggressively which results in sharing most of the traffic load among few active radios. This may increase end-to-end packet delay and decrease in throughput for flows going through more congested nodes. However results show that EESM outperforms WES and PSM in terms of energy conservation and efficiency without significant impact on delays and throughput. EESM with $T_{th} = 65ms$ saves 15% energy per node compared to PSM. EESM with $T_{th} = 75ms$ and $T_{th} = 80ms$ saves 26.83% and 36.59% more energy per node respectively. Figure 5 shows there is slight increase in packet delay for aggressive EESM in order of milliseconds but goodput remains approximately similar. As long as there is low to medium traffic load in the network, energy saving mechanisms have better opportunities to conserve energy by putting more radios into sleep. With higher traffic density, more radios are required to keep the traffic flowing without unwanted delays hence giving less chances for switching states of radios. In case of fully saturated network, PSM and EESM will eventually converge with WES by keeping all radios ON. This behaviour is evident where energy efficiency is degrading in PSM and EESM as the number of traffic flows increases in the network.

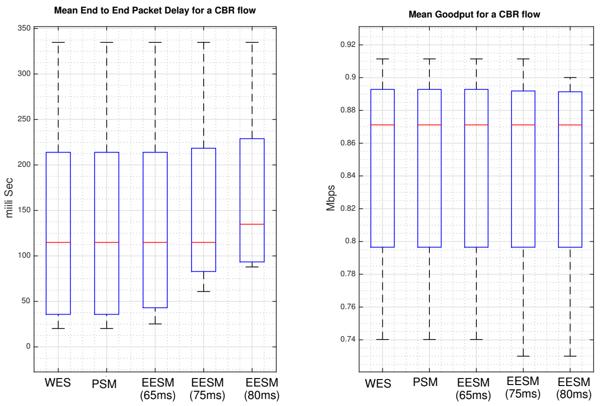

Fig. 4. Mean Packet delay and Goodput for a CBR flow

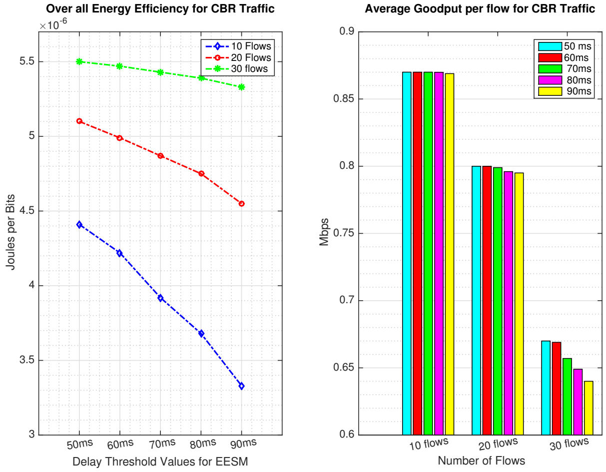

Fig. 5. Comparison of Energy Efficiency and Goodput for different number of CBR flows

B. *HTTP Traffic using TCP*

In second case, ten HTTP flows were generated randomly. Out of ten, four flows are directed to two gateways and rest are peer-to-peer. Having TCP as its underlying protocol, HTTP communication is connection based and slower than UDP traffic. TCP controls the data flow based on link quality and when congestion on a node tries to adjust the flow rate to avoid packet losses. For low to medium traffic in the network, this behaviour of TCP does not interfere with energy saving mechanism. Figure (6&7) show similar tendency for HTTP flows as for CBR traffic in terms of energy efficiency and network performance. The decrease in goodput is more obvious because of slower data rates of HTTP flows.

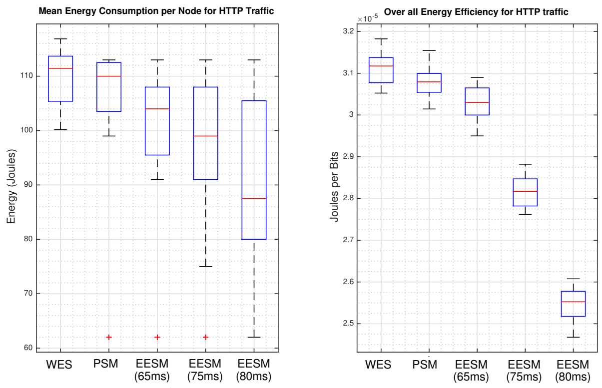

Fig. 6. Comparison of Mean Energy Consumption per node and Overall Energy efficiency of Network for HTTP Traffic

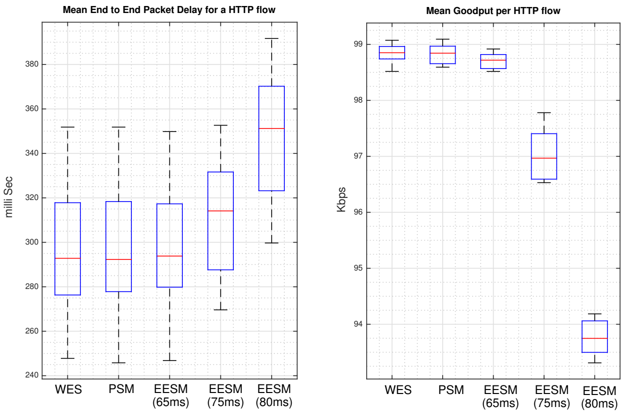

Fig. 7. Mean Packet delay and Goodput for a HTTP flow

With $T_{th} = 65ms$, at the cost of a small delay of few milli seconds and 0.3% drop in goodput, EESM achieves 2.5% better energy efficiency than WES or PSM and saves 5% energy per each node. Using $T_{th} = 75ms$ which incurs 10% increase in packet delay and 2.02% drop in throughput, EESM saves 10.9% energy at each node and improves energy efficiency by 8.9%. $T_{th} = 80ms$ saves even more energy per node (20%) but at the cost of approximately 7% drop in throughput and 15% increase in end to end packet delay.

In case of high traffic density if nodes put their radios to sleep more aggressively, TCP detects the increase in processing delay over active radios and slows down the flow rates as shown in Figure 8. Switching delay T_{del} does not change with this decrease in flow rate but over all end to end delay increases and throughput drops. Adjusting the threshold value according to traffic density in the network can mitigate this problem.

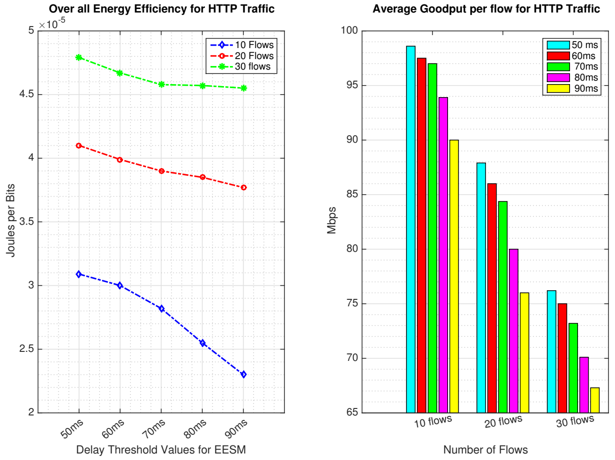

Fig. 8. Comparison of Energy Efficiency and Goodput for different number of HTTP flows

V. CONCLUSION

To improve the energy efficiency of multi-radio multi-channel wireless mesh networks, we have proposed EESM, the enhanced energy savings mechanism. We assume that each node in a network has a dedicated receiver radio with a known channel, and multiple transmitter radios. Based on observed flow rates and delays, a node may put individual transmitters to sleep; nodes wake up transmitters again once sufficient congestion is observed. An empirical evaluation demonstrates that EESM can save significant energy over the default power saving mode (PSM), without degrading network performance for both constant bit rate flows and HTTP traffic, for low and medium traffic loads. As the traffic load increases, energy efficiency begins to decrease, and EESM eventually converges to PSM. Different choices of a threshold parameter for EESM gives different tradeoffs between energy consumption and network performance. For delay tolerant traffic, a higher value of the threshold is recommended to conserve energy. In future work, we will investigate dynamic selection of the threshold values in response to changing flows rates in TCP, and we will investigate flow-specific thresholds, in order to achieve different QoS performance as required by different applications.

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REFERENCES

[1] Shengyang Chen and Gabriel-Miro Muntean. E-mesh: An energy-efficient cross-layer solution for video delivery in wireless mesh networks. In *IEEE international Symposium on Broadband Multimedia Systems and Broadcasting*, pages 1–7, 2012.

[2] Soumya Dey, Himanshu Sarmah, Subhadeep Samantray, Devraj Divakar, and SS Pathak. Energy efficiency in wireless mesh networks. In *Computational Intelligence and Computing Research (ICCIC), 2010 IEEE International Conference on*, pages 1–4. IEEE, 2010.

[3] Lúcio Studer Ferreira and Luís M Correia. Energy-efficient radio resource management in self-organised multi-radio wireless mesh networks. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, pages 232–236. IEEE, 2011.

[4] Vaibhav Garg, Kotaro Kataoka, and Siva Subramanya Rohith Talluri. Performance evaluation of wireless ad-hoc network for post-disaster recovery using linux live usb nodes. In *Wireless and Mobile Computing, Networking and Communications (WiMob), 2015 IEEE 11th International Conference on*, pages 125–131, 2015.

[5] Christian Köbel, Walter Baluja Garcia, and Joachim Habermann. A survey on wireless mesh network applications in rural areas and emerging countries. In *Global Humanitarian Technology Conference (GHTC), 2013 IEEE*, pages 389–394, 2013.

[6] Sarra Mamechaoui, Fedoua Didi, and Guy Pujolle. A survey on energy efficiency for wireless mesh network. *Computer Networks & Communications*, 5(2), 2013.

[7] Christian Mannweiler, Pratip Chakraborty, Andreas Klein, and Hans D Schotten. Solarmesh-deployment aspects for wireless mesh networks in developing countries. In *International Conference on e-Infrastructure and e-Services for Developing Countries*, pages 105–114. Springer, 2012.

[8] TN Nagabhushan, SP Shiva Prakash, and Kirill Krinkin. Power saving routing algorithms in wireless mesh networks: A survey. *Converence of FRUCT association*, 2013.

[9] M. A. Nezhad, L.ç Cerdà-Alabern, B. Bellalta, and M.G Zapata. A semi–dynamic, game based and interference aware channel assignment for multi–radio multi–channel wireless mesh networks. *International Journal of Ad Hoc and Ubiquitous Computing*, 14(3):200–213, 2013.

[10] M. Portmann and A. A. Pirzada. Wireless mesh networks for public safety and crisis management applications. *IEEE Internet Computing*, 12(1):18–25, 2008.

[11] SP Prakash, TN Nagabhushan, and K. Krinkin. Energy aware power save mode management in wireless mesh networks. In *Open Innovations Association (FRUCT), 2013 14th Conference of*, pages 122–131. IEEE, 2013.

[12] SP Shiva Prakash, TN Nagabhushan, and Kirill Krinkin. Energy aware power save mode based aodv routing for ieee 802.11 s wireless mesh networks. *Energy*, 137(4), 2016.

[13] P. Serrano, A. Garcia-Saavedra, G. Bianchi, and A. Banchs, A.and Azcorra. Per-frame energy consumption in 802.11 devices and its implication on modeling and design. *IEEE/ACM Transactions on networking*, 23(4):1243–1256, 2015.

[14] Jianfeng Wang, Yuguang Fang, and Dapeng Oliver Wu. A power-saving multi-radio multi-channel mac protocol for wireless local area networks. In *Proceedings INFOCOM 2006. 25TH IEEE International Conference on Computer Communications*, pages 1–12, 2006.

[15] A. Yarali, B. Ahsant, and S. Rahman. Wireless mesh networking: A key solution for emergency & rural applications. In *Advances in Mesh Networks, 2009. MESH 2009. Second International Conference on*, pages 143–149. IEEE, 2009.