Power Aware Metrics For HWMP in 802.11s

D. Yuranov
Open source and Linux Lab
Saint-Peterbutg, Russia
d.yuranov@gmail.com

A. Rudakova
Open source and Linux Lab
Saint-Petersburg, Russia
aerorina@gmail.com

Abstract

The article represents the results of comparative analysis of existing routing protocols in wireless networks in the context of nodes power characteristics regard and the possibility of adaptation to the specific work of mobile devices with limited power supply. Considered are the experimental results of batteries energy expense in case of different exchange intensity of the mesh connection established for the different IEEE 802.11s modes. The power aware metrics extensions are suggested and the problem of traffic optimization with the help of these metrics is defined.

INDEX TERMS: EPM, POWER AWARE NETWORKS, NETWORKING, ROUTING, WLAN, HWMP

I. INTRODUCTION

Every year the mobile devices power consumption grows while batteries cannot provide the demanded quantity of energy. This problem is connected with the limited capacity of the applied accumulator elements. So there are two ways of solving this problem. The extensive way lies in the growth of accumulator elements power and the intensive one consists in the optimization of the storages' energy consumption.

The first way is limited by the technical aspects of the accumulator elements production and by the vendors’ requirements to the mobile devices sizes. The second way is more preferable due to the possibility of realization regardless of capacitive elements' production technology. However it demands deep knowledge of the problem especially such its aspects as the reason and the amount of energy consumption by devices’ components. The power consumption system’ bottleneck detection will help to concentrate on the right solving method and to decrease batteries power consumption at most effectively. The further investigation is dedicated to this method.

II. MAIN PART

Due to the mobile devices’ sizes and portability they are used as the network access means for information retrieval and communication with other devices more and more frequently. The new promising class of such networks is actively investigated nowadays Multi-Hop Wireless Mesh Network.

In Mesh Networks routing, and especially energy-effective routing, is the key problem and main design criteria because of the nodes' dynamics and the network distributed structure. When routing in Mesh Network is active the mobile nodes with limited energy supply have a critical impact on the whole network stability and fail safety.

We carried out the experimental research on the reasons of different accumulators’ power consumption by the mobile devices in different operating modes in wireless network. The results are represented in fig. 1.

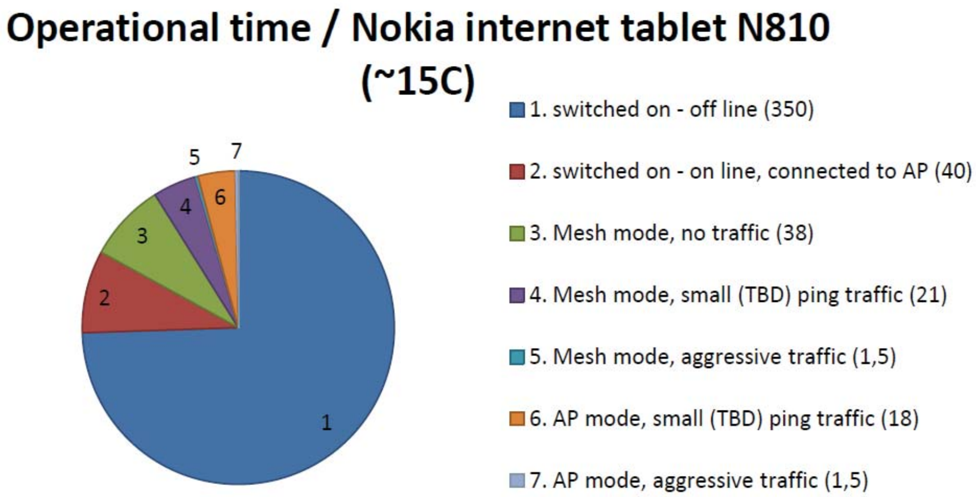

Fig. 1. Operating time of Nokia internet tablet N810 (~15C)

As one can see from the given diagram the device lifetime is longest when it operates in mode 1 with the turned off network interface. In this mode the device consumes the minimal amount of battery energy. The most energy-dependent modes are the 5^{th} and the 7^{th} modes with active traffic transmission which lead to minimal device lifetime of 1.5 hours in general. In these modes the device consumes the most part of power when it receives, retransmits and waits for data through its network interface.

According to the foregoing the decrease of the mobile devices power consumption can be achieved by the development of energy-effective Mesh Networks protocol.

At the moment a number of approaches to nodes energy preservation is already developed and investigated [1]. Mobile nodes expend energy not only while active sending and receiving data but also in wait condition while active environment listening in order to get messages from other nodes. That is why the entire node's spent energy during the communication process in the network can be divided into two types:

- Active Energy Communication – a node's energy needed for sending and receiving data;
- Inactive Energy – energy spent by an inactive node on environment listening to incoming signal.

In reliance upon suggested spent energy types it is possible to choose 3 approaches to power preservation. The first type is focused on wait energy saving, the last two ones – on communication energy.

- Sleep/Power-down Mode Approach;
- Transmission Power Control Approach lies in level tuning of every node's signal so that a message could reach the nearest neighbor node;
- Load Distribution Approach lies in energy preservation due to low energy nodes skip while choosing the route to the destination node.

The first approach, Sleep/Power-down Mode Approach, is targeted at wait energy preservation owing to temporary switching between nodes' active and sleep (idle) or off conditions. However if all the nodes are off they cannot listen the environment and therefore cannot receive incoming packets. One of possible solutions is a special controlling node (also called a master node) determination. Such node coordinates all other (slave) nodes' interaction. Having chosen such a node the slave nodes can stay asleep until they are sent data.

In multi-hop networks one controlling node is not enough to cover such a vast network. There are 2 schemes of such network organization. The first one is a symmetric model with a controlling node of the same level as its dependent nodes. The second scheme is called asymmetric as its controlling node has a bigger action range thanks to increased level of transmitting signal in comparison with its dependent nodes, so the master node can cover a bigger number of neighbor nodes. This method of power saving is actively investigated nowadays as there are still some problems with such tasks as controlling node choosing and master-salve scheme maintenance in high-dynamics network.

It is also possible to reduce active energy expenses by tuning each node's signal level to the level necessary for a message to reach the nearest neighbor. This solution uses the method of Transmission Power Control Approach which allows optimal route defining by reducing the transmission up-to-the-destination energy spent. Another method targeted at reducing the communication energy is the Load Distribution Approach. Its main target is balancing of power expenses on transmissions between network nodes. As low-power nodes are excluded while forming a route to the destination node, it leads to the increase of Network Lifetime thereby.

Each approach having its own advantages and disadvantages suits to one or another situation. However the best solution of energy expenses decrease problem is a combination of these methods and development of more effective routing protocol able to preserve nodes' power.

To appraise the current condition of power saving problem in existing [2], [3] wireless networks routing protocols we have made a comparative analysis from the point of view of nodes' power characteristics. The analysis used the fore-cited protocol metrics and power save methods. The results are presented in table 1.

TABLE 1.
THE COMPARATIVE ANALYSIS OF EXISTING ROUTING PROTOCOLS.

Parameter	Proactive protocols		Reactive protocols		Hybrid protocols	
	DSDV	OLSR	AODV	DSR	ZRP	HWMP
Routing algorithm	Distance Vector	Link State	Distance Vector	Link State	Distance Vector	Link State
Route search	O(d)	O(d)	O(2d)	O(2d)	Intra: O(I) Inter: O(2d)	Intra: O(I) Inter: O(2d)
Metrics	Shortest path					Airtime
Load Distribution Approach	No					
Transmission Power Control Approach	No					
Sleep/Power-down Mode	No					Yes

As a result it was found out there are no methods for nodes power saving. Only HWMP, a Mesh Networks routing protocol, describes the possibility to save power by periodical toggling of active and sleep modes [4]. This is possible because Mesh Network nodes are obliged to report about their ability to support sleep (power-saving) mode. It is realized by use of capability information field in beacons and in probing packets responses. The same field also informs whether a node acts in power-saving mode or it has a connection with power-saving node.

Hybrid protocols in contrast to pure active and proactive ones can potentially provide high network scalability. They try to reduce a number of nodes participating in broadcast forwarding by structure detection what helps nodes to act together in order of routes establishment. Working together the most or just more suitable nodes can initiate a search of the route to the destination.

In hybrid protocols nodes interconnection peculiarities can cause longer routes saving, for instance, when all nodes of a single zone act together to maintain local information about all nodes in this zone. Zones presence potentially can eliminate the necessity of frequent broadcast packet transmissions as nodes know where to search a destination node at all times. Hybrid protocols have another advantage: they try to eliminate one destruction point and prevents the appearance of network “bottleneck” problem. It is achieved by providing any node with the possibility to route or forward data in case the preferable node's denial happens.

Subsequent to the results of the comparative analysis of the existing routing protocols and the received experimental results of a mobile device power expenses we defined the corresponding goal: development of a metric considering nodes power possibilities as an extension of HWMP routing protocol.

The problem of a routing metric development is a problem of optimal path search [4] from point of view of the nodes power consideration. In this occasion it is a task of maximum bandwidth path search during a given time interval [0,t], so being given a load profile of battery S it is needed to solve task A:

$$(A)\ argmax_R\ J(P,S,R,\zeta,t)$$
$$\theta(l) \geq c(l), \forall l \in L$$
$$P^{max}(l) \geq P(l) \geq 0, \forall l \in L$$
$$\varepsilon_n, \forall n \in N$$

where $J(P,S,R,\zeta,t)$ is a number of successfully delivered packets during time interval [0,t] when route R was chosen as a new data stream ζ, P is network interface's transmission power, $\theta(l)$ is signal/noise factor of a transmission channel l, $c(l)$ is minimal signal/noise factor requirement for channel l, and ε_n is remaining power or node's n lifetime.

The ε_n value is one of the most important limitations of the problem. Its definition can be done in several ways. One of such ways is analytical model employment.

The two most important properties of a battery are its voltage (expressed in volts, V) and its capacity (mostly expressed in Ampere-hour, Ah); the product of these two quantities is a measure for the energy stored in the battery. In an ideal battery its potential stays the same up to the moment of the battery's full discharge and becomes zero then. And the ideal accumulator battery's capacity is constant under any load. But in real life the accumulator potential reduces with charge decrease and the bigger the load upon the accumulator is the less its capacity becomes. This phenomenon is called an effect of battery's capacity level change.

In an ideal occasion the battery's lifetime is pretty easy to estimate. In case of constant load level the accumulator lifetime L is estimated as battery capacity C divided by current strength I:

$$L = \frac{C}{I}$$

Owing to nonlinear nature of battery's parameters changing during the process of its discharge this expression cannot be used to define battery lifetime. In case of constant load the lifetime can be evaluated more precisely with the help of Peukert's Law:

$$L = \frac{a}{I^b},$$

where a > 0 and b > 1 are an accumulator-dependent constants. In case of variable accumulator load level i(t) Peukert's Law takes on the next form:

$$L = \frac{a}{\left(\frac{1}{L}\int_0^L i(t)dt\right)^b}$$

It seems that thanks to this formula it is possible to count the lifetime of a battery with different load profiles. However the experimental result show it is quite untrue. The reason of it is an effect observed in batteries during their exploitation. It is *a recovery effect* which lies in the accumulator possibility to regenerate a part of its spent capacity during a certain time period.

In view of the difficulty of precise determination of battery lifetime when loads are non-constant a number of analytic models was developed. Given a set of incoming parameters these models can evaluate accumulator lifetime L with account of the recovery effect and changes of the battery capacity level.

One of such analytic models was described [5] by Daler Rakhmatov, Sarma Vrudbula and Sarma Vrudbula in 2001. The model represents the process of changes of electro-active ions concentration in an electrolytic conductor what allows to evaluate the lifetime of a certain-load battery.

In the general case battery lifetime can be defined as time when a certain quantity value jumps over a certain threshold. Traditionally such a quantity was the potential level on the electrical battery terminals. So battery lifetime is time needed for battery potential to become lower than a certain limitary value. The Rakhmatovś model relates accumulator lifetime with its time-dependent load also taking into account the changes of electro-active ions concentration as a function of load.

Rakhmatov at al. considered 2 main processes into the battery: electrochemical electrode surface reaction and electrolyte ionic diffusion. They used Faradayś Law to describe the reaction behavior. The suggested model is an analytic solution of 2 diffusion equations and of 3 constraint equations:

$$-J(x,t) = D\frac{\partial C(x,t)}{\partial x}, \frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2},$$
$$-J(0,t) = \frac{i(t)}{vFA}, J(w,t) = 0, C(x,0) = C_i \qquad (1)$$

$J(x,t)$ and $C(x,t)$ are electro-active ions flow and concentration respectively and are dependent from time t and distance x from the electrode surface. D is a diffusion index, v – a number of electrons taking part into the chemical reaction, A – the electrode square, F – is the

Faradayś constant, w – the length of diffusion area, and C_i - the value of the initial concentration in balance condition. The battery is considered to be discharged at time t=L when the value C(0,t) becomes lower than some threshold C_{cutoff} .

The solution (1) includes forward and inverse Laplace transformation and theta-function and has the following best possible form:

$$\alpha = \int_0^L i(\tau)d\tau + 2\sum_{m=1}^{\infty}\int_0^L i(\tau)e^{-\beta^2 \cdot m^2 \cdot (L-\tau)}d\tau \tag{2}$$

$$где\ \alpha = vFAw\left(C' - C_{cutoff}\right) и\ \beta = \frac{\pi\sqrt{D}}{w}$$

The unit of α is coulomb (charge) and that of β^2 is second^{-1}. Intuitively, α is the battery capacity, and β is the measure of battery nonlinearity. As it can be seen from the equations (2) α increases as Aw (i.e. the battery size) increases. Also, β decreases as D decreases. A larger value of β indicates a better battery. And really, if β is sufficiently large, the second term of the equation (2) becomes negligible. So we obtain the model of an ideal power source.

Under constant-current discharge, i(t) = I, the equation (2) reduces to the following form:

$$\alpha = I \cdot \left[L + 2\frac{\sum_{m=1}^{\infty} 1 - e^{-\beta^2 \cdot m^2 \cdot L}}{\beta^2 \cdot m^2} \right] \tag{3}$$

For a general case, the time-varying discharge current i(t) approximates by n-step piece-wise constant load. After substitution of i(t) into (2) and integrating the sum term by term (the series is absolutely convergent), we obtain

$$\alpha = \sum_{k=0}^{n-1} I_k F\left(L, t_k, t_{k+1}, \beta\right),$$

$$where\ F\left(L, t_k, t_{k+1}, \beta\right) = t_{k+1} - t_k + 2\frac{\sum_{m=1}^{\infty} e^{-\beta^2 \cdot m_2 \cdot (L - t_{k+1})} - e^{-\beta^2 \cdot m^2 \cdot (L - t_k)}}{\beta^2 \cdot m^2} \tag{4}$$

It is worth noting that $t_0 = 0$ and $t_n = L$. For n =1, the equation (4) becomes the special case (3). The magnitude of the series terms in (3) diminish very rapidly as m grows. The experimental results got by Rakhmatov at al. indicate that employing only the first 10 terms already yields quite accurate lifetime predictions.

The model described by equation (4) is rather good in terms of accuracy and computational complexity.

As the equation (4) describing battery capacity α is difficult to evaluate with such a parameter as battery lifetime L, Rakhmatov and others suggested an algorithm of this parameter evaluation for different load profiles. The incoming algorithm parameters of lifetime evaluation are a set of loads S_l , their timings S_t and characteristic battery parameters α and β . The algorithm output is a set of 2 elements where the first element is nodeś failure time and the second one second element denotes the differences between the n-term sum and α in equation 4.

On basis of the formulated optimization problem and the analytical model we suggested a metric of path search which accounts nodes' batteries lifetimes.

With the help of Rakhmatovś analytic model each node evaluates its lifetime L from the variable current strength i(t). The node does it periodically with frequency f. It is possible to use current node lifetime L as a node cost metric in accordance with the following rule: the more L is, the better and more logical solution it is. The longer a node can exist until its full log-off, the longer it can interact with other network nodes and therefore influence the whole network lifetime. But in some cases 2 different nodes can have the same lifetime L values. Then the preferred node is a node with bigger maximum lifetime as it means its battery capacity is bigger.

Theoretical maximum battery lifetime L_{max} is evaluated by the following formula:

$$L_{max} = \frac{C}{I_{min}},$$

where C is nominal battery capacity according to its specification, I_{min} is minimal load of battery current strength in wait condition with turned off network interface.

Accounting for L_{max} the formula of metric value M_E evaluation is:

$$M_E = 1 - \frac{T_e}{T_{max}} = 1 - \frac{L_{max} + L^2 / L}{T_{max}} = \frac{L_{max} + L^2}{L \cdot T_{max}},$$

$$where \ \ T_e = \frac{L_{max}}{L} + L = \frac{L_{max} + L^2}{L}$$

where T_{max} is a maximum quantity T_e value, introduced to cast M_E values diapason to [0,1].

The suggested metric is isotonic what is necessary and enough [6] for searching minimum weight paths by Bellman-Ford and Dijkstra algorithms.

According to IEEE 802.11s standard HWMP protocol sets radio-aware Airtime Link Metric by default which shows the amount of resources necessary to transmit a frame to the neighbor node through the given channel. Let us denote it as M_{ALM} . The metric is evaluated as the cost of a frame transmission through the certain channel according to the following formula:

$$M_{ALM} = \left(O + \frac{B_t}{r} \right) \cdot \frac{1}{1 - e_{pt}},$$

where O is channel access overhead including frame headers and access protocol frames; B_t – a number of bits in test frame; r – data transfer rate in Mbps which is used to transmit a middle-sized frame with size B_t . This size depends from the current state which evaluation depends on the used adoption of data transfer frequency. And e_{pt} is the probability of a frame damage during its transmitting with rate r because of a radio broadcasting error. The method of e_{pt} evaluation depends on the certain protocol realization.

Existing Airtime Link Metric can be accompanied by the new power-aware metric. The full metric gets the following form:

$$M = M_{ALM} + kM_E,$$

where k is a weight factor. To rule the metric contribution to the aggregate metric the only weight factor k should be tuned.

A metric is an evaluation of a node lifetime level: the less the metric value is, the longer the accumulator lifetime is.

III. Conclusion

We have presented the results of comparative analysis of existing routing protocols in wireless networks. Considered are the experimental results of batteries energy expense in case of different exchange intensity of the mesh connection established for the different IEEE 802.11s modes.

The result metric is a suggestion of HWMP protocol extension and demands its efficiency investigation. The further work will be targeted at its efficiency and applicability investigation and at the problem of traffic optimization using this metric.

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