Analytical Study of Link Management in IEEE 802.11s Mesh Networks

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Abstract

Efficient link management is important for mesh networking. The links opened between neighbor STAs should be stable and ensure high probability of packet delivery. Various approaches of link management are usually compared by simulation. The core contribution of this paper is original link management efficiency criteria and an analytical model of decision-making process of link management in IEEE 802.11s, which are used to improve network performance.

I. Introduction

Self organizing wireless networks (mesh networks or MANET: Mobile Ad-hoc NETworks) have attracted much interest of researchers and telecommunication companies. In such networks, neighbourhood discovery and link management are crucial issues. In both static and mobile scenarios, the quality of the wireless channel between neighbour stations (STAs) is changing continuously. To achieve high throughput and to meet QoS requirements, only stable and reliable links between STAs shall be opened.

Various protocols have been developed for this purpose. IEEE 802.11s amendment[1] for mesh networking to IEEE 802.11 standard [2] describes the Mesh Peering Management protocol (MPMP). Although the main purpose of this protocol is establishing, maintaining and tearing down mesh peering, it is also used for link management. By special frame handshake, STAs may open or close links with neighbours and thereby change link *states*. STAs make decision of the handshake initiation by analyzing series of received and missed beacons, which are periodically broadcast by every STA. Link management strategy and possible methods for beacons series analysis are out of the scope of the amendment.

Since the amendment was approved in September 2011, no papers studying MPMP were published yet. So we consider several papers ([3],[4] and [5]) about Neighbourhood Discovery Protocol (NHDP) [6] which is a part of well known routing protocol OLSR [7]. Like MPMP, NHDP makes decision about link state by analysing series of periodically broadcast HELLO-messages which are similar to beacons. However unlike MPMP, NHDP does not use any handshake mechanism.

In [3], authors study how the interval between two consecutive HELLO-messages influences the throughput of the network running with OLSR. When this interval is small, STAs quickly discover neighbours and open links with them. But frequent HELLOs increase overhead and degrade network throughput.

In mobile networks, M. Voorhaen and C. Blondia [4] suggest to use short HELLOs which are sent more frequently than default HELLOs. STAs decide to open/close a link with its neighbour after receiving/missing only one beacon. This strategy hastens the protocol reaction on topology changes but also causes fluctuation of link states which increases routing errors.

In these papers, efficiency of link management is studied indirectly by simulation or by test-bed experiments using high-level performance indices (e.g. throughput, packet delivery ratio) influenced also by many other mechanisms.

One of the first attempts to develop an analytical model of link management is made in [5]. In the paper, authors study such values as link lifetime, discovery delay (the interval between the moment when a STA enters the transmission area of another one and the moment when the STA is discovered), and dead time (the delay of detecting a broken link). Using their model the authors compare different beaconing schemes: when beacon interval is fixed and when it is exponentially distributed. Fixed beacon intervals are shown to be more efficient according to the proposed indices. An important shortcoming of this work is the raw error rate model: the probability of a beacon transmission failure is considered to be either 0 or 1 depending on the distance between STAs, while in real networks, it increases *gradually* from 0 to 1 with the distance between STAs. In this paper, we propose an analytical method for MPMP efficiency evaluation which removes this shortcoming.

The rest of the paper is organized as follows. Section II describes MPMP. We consider 2 strategies of making decision about link state: traditional one and proposed one. Section III introduces original criteria of link management efficiency. To evaluate these criteria, we develop an analytical model of MPMP in Section IV. Some numerical results and discussion on comparing MPMP with different strategies are presented in Section V. Final conclusions are given in Section VI.

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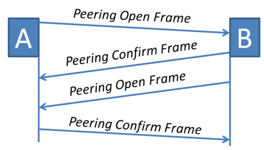

Fig. 1. MPM frames handshake

II. MPMP

MPMP defines the following procedure of opening/closing links. To open a new link, a STA sends Peering Open Frame (see Fig. 1). After receiving this frame, another STA replies with both Peering Confirm Frame and its own Peering Open Frame. Then the first STA sends Peering Confirm Frame and the link is considered as open by both STAs[1]. If a STA decides to close an existing link, it sends Peering Close Frame. Peering management frames are unicast and acknowledged. Due to 802.11 retry mechanism these frames are delivered with high probability and, hence, the state of the link is synchronized on both STAs.

IEEE 802.11s amendment does not define conditions when a STA decides to open new link or close the existing one. In the paper, we consider two strategies which we refer to as MPMP with unconditional confirmation (MPMP-U) and MPMP with conditional confirmation (MPMP-C).

MPMP-U is based on the following set of rules:

1) STA A decides to open a new link with STA B after receiving r beacons in a row from B.
2) STA A decides to close an existing link with STA B after missing s beacons in a row from B.
3) After receiving Peering Open Frame (a) or Peering Close Frame (b) STA A *always agrees* with the decision made by B.

Similar approach is used in the implementation of Linux Wireless driver [8], in the popular network simulator ns-3 [9], in OLSR [7] and TBRPF [10] routing protocols.

IEEE 802.11s [1] allows a STA to reject opening a new link after receiving Peering Open Frame. This allows us to develop **MPMP-C** strategy by replacing rule 3a) with the following one.

3a') When STA A receives Peering Open Frame from STA B, it opens a link with B only if A has received not less than l beacons from B in a row by this moment. Otherwise, A refuses to open the link.

When $l \geq r$ the first attempt to open the link is always unsuccessful. Consider the situation when STA A receives r B's beacons in a row earlier than STA B does. When A sends Peering Open Frame, STA B has not received more than $r-1$ beacons and it refuses to open the link. Hereby, choosing $l \geq r$ results in unnecessary overhead and should not be used.

When $l = 0$, MPMP-C works in the same manner as MPMP-U. While l grows, the percentage of link opening rejects increases and the difference between two strategies of MPMP becomes more significant. To evaluate the difference between two strategies, we choose for each r the highest possible value of l which is $l = r - 1$.

III. MPMP Efficiency Criteria

As mentioned in Section I, an effective MPMP shall open and maintain only reliable stable links. Moreover, such links shall be opened as soon as possible. Further in this section we define these requirements in the form of mathematical constraints.

Let $T_{open}(p)$ and $T_{close}(p)$ be the average durations of open and close states with given probability p of successful frame transmission[2]. As open and close states alternate, probability $\pi(p)$ to find the link in the open state is calculated as follows:

$$\pi(p) = \frac{T_{open}(p)}{T_{open}(p) + T_{close}(p)}. \tag{1}$$

An efficient MPMP shall meet the following requirements.

Open links shall be **reliable**, i.e. provide probability p of successful frame transmission higher than pre-defined threshold p_0. So the links with $p > p_0$ shall be mainly open ($\pi(p) > \frac{1}{2}$) while links with $p < p_0$ shall be mainly close ($\pi(p) < \frac{1}{2}$), that is

$$\pi(p_0) = \frac{1}{2}. \tag{2}$$

If p does not change, link states shall be **stable**, i.e. shall not fluctuate. Link fluctuation g can be defined as

$$g(p) = \frac{1}{T_{open}(p) + T_{close}(p)}. \tag{3}$$

[1]MPM opens only bidirectional links.

[2]To make our model more tractable, we assume that this probability is the same for both directions and for data frames and beacons.

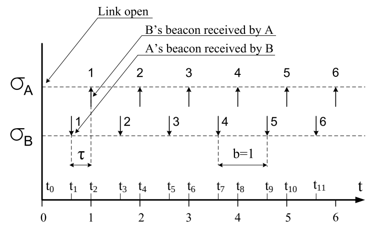

Fig. 2. Sequences of beacons received by STAs A and B

The value $\frac{1}{2g(p)}$ is the average time between two consecutive changes of the link state. For routing information to be correct and up-to-date, it is necessary that

$$\forall p < 1 \Rightarrow \frac{1}{2g(p)} \gg T_{update}, \tag{4}$$

where T_{update} is the topology update interval.

Finally, we use **discovery delay** as the third efficiency index. We slightly change the discovery delay definition given in [5] to make it useful in our case. Consider a mobile network. Discovery delay T_{delay} is the delay from the point of time when p reaches threshold p_0 to the time when the link is opened. Discovery delay is caused by the necessity of collecting beacons statistics. Obviously, the link shall be opened much earlier than the link becomes unreliable again. In other words, the following requirement shall be met:

$$T_{delay} \ll T_{link}, \tag{5}$$

where T_{link} is the physical link duration that is the average interval while $p \geq p_0$. In mobile networks with moderate mobility where p changes gradually with time, $T_{delay} \sim T_{close}(p_0)$. In mobile networks with high mobility where p changes dramatically with time, $T_{delay} \sim r$.

These criteria are used to compare MPMP strategies and to configure MPM for any specific purpose. To estimate all indices introduced in this Section, it is sufficient to find $T_{open}(p)$ and $T_{close}(p)$ which is done in Section IV.

IV. Analytical Model

Since every STA schedules its beacons to be broadcast strictly periodically and the interval b between two consecutive beacons is the same for every STA, we choose b as the model time unit.

Let us consider two neighbour STAs A and B. Let B transmit its beacon τ time units after STA A's beacon, where τ is a random value uniformly distributed in the interval $[0, 1)$. The value of τ is fixed when the STAs switch on.

Firstly, let us calculate T_{open}.

A. Estimation of the Average Open State Duration

At $t_0 = 0$, STA A receives a beacon from STA B and opens the link. Let $\{\sigma_t\}_1^\infty$ represent the series of beacons, where $\sigma_t = 1$ if a beacon is received at moment t, and $\sigma_t = 0$, otherwise. Let us call finite sequence $\{\sigma_t\}_1^n$ of length n s-regular if it does not include s zeroes in a row.

Let $\phi_{s,p}(n)$ be the probability that sequence $\{\sigma_t\}_1^n$ is s-regular. It is apparent that $\phi_{s,p}(n) = 1$ if $0 < n < s$. For further analysis we also define $\phi_{s,p}(0) = 1$. For $n \geq s$ $\phi_{s,p}(n)$ is calculated according to the following Lemma, which proof is omitted because of the paper size limitation.

Lemma 1: *Given p,*

$$\phi_{s,p}(n) = p \sum_{i=0}^{s-1} (1-p)^i \phi_{s,p}(n-i-1), n \geq s. \tag{6}$$

$\phi_{s,p}(n)$ yields the probability that the STA does not decide to close the link before its neighbour's beacon $\#(n+1)$. To calculate the probability that the link is still open, we need to consider series of beacons of both A and B. Sequences of beacons ($\{\sigma_t^A\}$ and $\{\sigma_t^B\}$) received by A and B after t_0 are shown in Fig. 2.

After STA B sends its beacon $\#n$, the link remains open only if the link was not closed before either by A or by B. By this moment, STA A has also sent n beacons. The probability $P_A(n)$ that the open state duration t_{open} exceeds n is $P_A(n) = \phi_{s,p}^2(n)$. STA A transmits its beacon $\#n$ at the moment $t = n - \tau$. By this moment, B has sent only $n-1$ beacons. The probability $P_B(n)$ that t_{open} exceeds $n - \tau$ is $P_B(n) = \phi_{s,p}(n)\phi_{s,p}(n-1)$, $n > 0$.

Thus, the average open state duration is determined by

$$T_{open,\tau}(p) = 1 - \tau + \sum_{k=1}^{\infty} \left\{ (1-\tau)\, P_A(k) + \tau P_B(k) \right\}. \tag{7}$$

Averaging $T_{open,\tau}(p)$ on τ, we obtain

$$T_{open}(p) = \frac{1}{2} + \frac{1}{2} \sum_{k=1}^{\infty} \left\{ \phi_{s,p}^2(k) + \phi_{s,p}(k-1)\phi_{s,p}(k) \right\}, \tag{8}$$

which holds for both MPMP-U and MPMP-C strategies.

B. Estimation of the Average Close State Duration

1) MPM-U ($l = 0$): The average close state duration is calculated similarly to $T_{open}(p)$. The link stays in the close state until one of the STAs receives r beacons in a row. The probability of beacon loss equals to $1 - p$. Substituting $1 - p$ for p and r for s in (8), we obtain:

$$T_{close}(p) = \frac{1}{2} + \frac{1}{2} \sum_{k=1}^{\infty} \left\{ \phi_{r,1-p}^2(k) + \phi_{r,1-p}(k-1)\phi_{r,1-p}(k) \right\}. \tag{9}$$

2) MPMP-C ($l = r - 1$): Suppose that at the moment $t_0 = 0$ STA A does not receive the next beacon from STA B and closes the existing link. From this moment, we consider an aggregated sequence of beacons $\{\sigma'_t\}_1^n$, which is formed in the following way. Even and odd subscripts are related to the beacons received by A and B, respectively. Again, "1" corresponds to a successfully received beacon, "0" corresponds to a lost beacon. The link remains in the close state until the aggregated sequence $\{\sigma'_t\}_1^n$ contains a subsequence with $l + r = 2r - 1$ ones in a row. It happens with probability $1 - \phi_{2r-1,1-p}(n)$. As even and odd subscripts correspond to different STAs, we obtain

$$T_{close}(p) = \frac{1}{2} + \frac{1}{2} \sum_{k=1}^{\infty} \phi_{2r-1,1-p}(k). \tag{10}$$

Given $T_{close}(p)$ and $T_{open}(p)$, all other parameters introduced in Section III may be easily calculated.

V. Numerical Results

A. Model Validation

To validate our mathematical model, we compare its results with the results obtained with well-known network simulator ns-3 [9]. We consider two Wi-Fi STAs, varying the distance between them. We set default values for all MAC parameters of 802.11a+s STAs, [2], [1]. We observe the link state during rather long lime (10000s while beacon period is 100ms) and run 50 repetitions for each selected combination of parameters to obtain statistically meaningful values of T_{open} and T_{close}. We find that the analytical and simulation results match with a good precision in a wide range of parameter values $p \in (0, 1)$, $r \geq 1$, $s \geq 1$ – see Fig. 3 where points and curves correspond to simulation and analytical results, respectively.

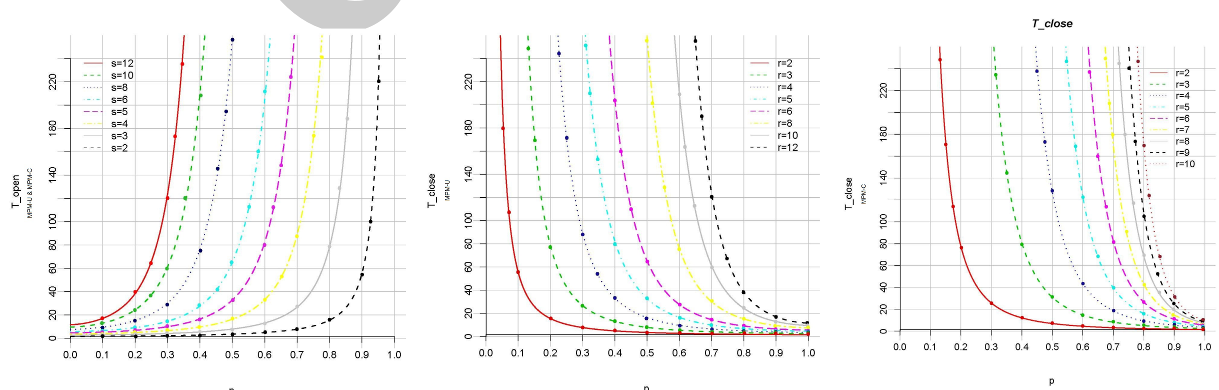

Fig. 3. $\langle T_{open}(p) \rangle$ for both strategies, $\langle T_{close}(p) \rangle$ for MPMP-U and MPMP-C with different r and s

TABLE I
CHOOSING THE OPTIMAL MPMP-U PARAMETERS

Velocity	T_{link}	Chosen (r,s)	$\frac{T_{close}(p_0)}{T_{link}}$	$\frac{\frac{1}{2g_{max}}}{T_{update}}$
0.005	246	(5,5)	0.13	0.12
0.01	123	(4,4); (5,5)	0.13; 0.26	0.25; 0.12
0.02	61	(4,4)	0.26	0.25
0.04	30	(3,3)	0.26	0.5

B. MPMP-U Adjusting

Let us demonstrate how to configure MPMP-U for the mobile network loaded with voice traffic. G.729 [11] codec generates 50 packets per second. According to the ITU recommendation [12], the quality of the received voice signal depends on the average packet delivery time, the jitter, i.e. the variation of the delivery time, and the packet loss ratio (PLR). In IEEE 802.11s nonoverloaded networks, the packets delivery time is much shorter than the required one, and PLR becomes the most important factor. According to [13], the quality of G.729 voice traffic is not fair if end-to-end PLR is higher than 10...12%. As PLR changes with time we measure PLR every interval $\Delta = 1$sec and define the unavailability of voice service, NV, as the probability that during this interval end-to-end PLR_Δ is higher than 10%, i.e. more than 5 packets of a flow are lost. As k packets are lost with probability $\frac{50!}{(50-k)!k!} PLR_\Delta^k (1-PLR_\Delta)^{50-k}$, to obtain low NV, say $NV = 1\%$, one shall provide PLR_Δ lower than 3%.

End-to-end PLR is calculated as follows: $PLR_\Delta = 1 - \left(1 - per^{\rho+1}\right)^D$, where per is the link packet error rate, $\rho = 7$ is IEEE 802.11 retry threshold, and D is the number of hops in the route. E.g. if $D \le 5$ for any route in the network, to achive PLR_Δ MPMP shall open links with $1 - per \gtrsim p_0 = 0.5$.

Let L be such a distance between 2 STAs that the probability of successful packet transmission between them is $p(L) = 0.5$. We locate 50 mobile STAs in the area $2.3L$x$2.3L$. With such high STA density, the network is almost always connected and almost all routes in this network are not longer than $D = 5$ hops. The STAs move according to 2D Random Direction Mobility Model [14] with moderate velocity $v = \{0.005, 0.01, 0.02, 0.04\}L$ per beacon interval[3], so the time interval when the distance between 2 STAs is less then L is $\langle T_{link}\rangle = \frac{\pi^2 L}{8v}$ [5].

The network works under IEEE 802.11s protocol with default parameters, however, instead of default HWMP routing protocol, we use a proprietary proactive link state hop-by-hop routing protocol broadcasting topology information with update interval $T_{update} = 4$ beacon intervals.

Thus, having determined p_0, T_{update} and $\langle T_{link}\rangle$, we can adjust MPMP-U.

At the first step, using (8) and (9) we find the set of pairs (r,s) which satisfy (2). They are (1,1), (2,2), (3,3), (4,4), ...

At the second step, we find $T_{close}(p_0)$ and $g_{max} = \max\limits_p g(p)$ for each pair in the selected set. As final values of MPMP-U parameters we may choose any pair which satisfies (4) and (5). For example, we choose such a pair that

$$\frac{T_{close}(p_0)}{T_{link}} \sim \frac{\frac{1}{2g_{max}}}{T_{update}}, \tag{11}$$

see Table I.

We run simulation using ns-3 [9] environment and prove that chosen pairs (r,s) provide better results than other values of MPMP parameters, see Fig. 4. Despite that we configured MPMP to achieve $NV \approx 1\%$, simulation results are worse because of drawbacks of other network protocols, e.g. routing errors.

The second result obtained with simulation is that several pairs provide almost the best network efficiency. E.g., when $v = 0.01$ using pairs (4,4), (5,5), (6,6) results in almost the same performance. It means that using equation (11) is not necessary. Any parameters values which meet both restrictions (4) and (5) provide good results.

Despite the optimal parameters values depend at least on the velocity, pair ($r = 4$, $s = 4$) gives good results in any considered scenarios. This fact, even leading to suboptimal results, is quite valuable for the real system design.

C. MPMP-C Adjusting

We have used proposed model to adjust MPMP-C in the similar manner. With our model we have obtained the following triads (r,s,l) of values: $\{(3,5,2)$, $(3,4,2)$, $(3,4,2)$, $(2,3,1)\}$ respectively for velocities $v = \{0.005, 0.01, 0.02, 0.04\}L$ per beacon interval. With simulation we have obtained that using MPMP-C provides the same NV as MPMP-U when the $v \le 0.02L$. When velocity is high, MPMP-C works much better than MPMP-U – see Fig. 4 for $v = 0.04$ and Fig. 5.

[3]Though $v = 0,04L$ may be hardly named as "moderate" velocity, we consider this value to show that the proposed method may be applied in a vast range of scenarios

The cause of this fact is that $\langle T_{delay} \rangle \sim r$ with high mobility. Fig. 6 shows the dependence of link fluctuation g at $p = p_0$ on r for both strategies. For any strategy, decreasing g leads to increasing r and thus increasing entry time. So, we cannot decrease both link fluctuation and entry time simultaneously. But for any r MPMP-C provides lower link fluctuation than MPMP-U with the same r. It means that proposed MPMP-C is a Pareto improvement of MPMP-U.

VI. Conclusion

In this paper, we consider theoretical aspects of MPMP, propose criteria to evaluate the efficiency of MPMP and develop an analytical model of decision-making mechanism. We apply the model to configure MPMP to achieve the best network performance and prove with simulation that this MPMP configuration provides the best results. We prove that MPMP with conditional confirmation is more efficient that MPMP with unconditional confirmation. Proposed approach allows to adjust MPMP optimally without long expensive testbed experiment or simulation, which motivates us to expand this approach on other link management protocols, e.g. NHDP[6]. This work will be done in the nearest feature.

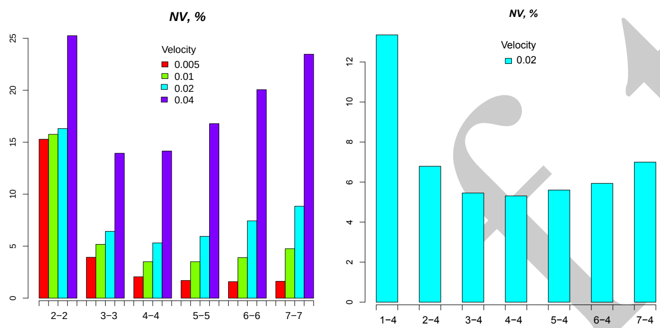

Fig. 4. NV for 3 voice flows and different protocol parameters $(r - s)$ and network mobility

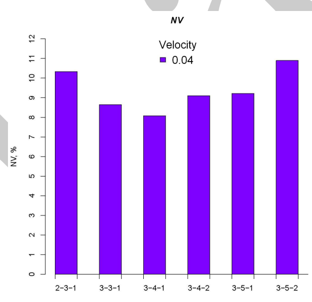

Fig. 5. NV for MPMP-C (velocity $v = 0.04L$)

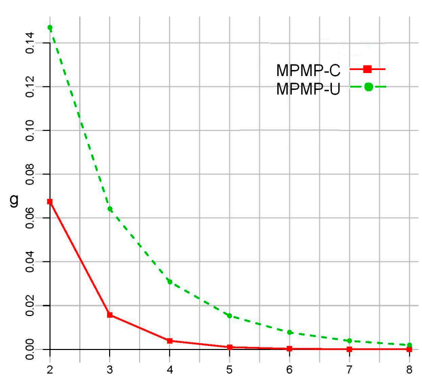

Fig. 6. $g(r)$ for MPMP-U and MPMP-C

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