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Abstract: We analyze the performance of *ad-hoc* routing as defined in MANet IETF working group in the random graph model. In particular we analyze the performance of a reactive protocol DSR and of a pro-active protocol OLSR. The random graph model is defined by the number of nodes n, and link probability p. We give the asymptotic evaluation of the flooding distance which is used in DSR and the multi-point relay flooding used in OLSR.

Key-words: Wireless network, mobile ad-hoc networks, flooding, mulit-point relays, random graphes, generating functions.

(Résumé : tsvp)

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Analyses des protocoles de routages dans les réseaux mobiles ad-hoc sous le modèle du graphe aléatoire

Résumé : Nous analysons les performances du routage ad-hoc tel qu'il est défini dans le sous-groupe de travail MANet de l'IETF. En particulier, nous intéressons au protocole réactif DSR et au protocole réactif OLSR. Nous avons recours au modèle du graphe aléatoire qui prend en paramètres le nombre de nœuds n et la probabilité de lien p. Nous donnons l'évaluation asymptotique de la distance d'inondation qui est utilisée par DSR et l'inondation par relais multi-points utilisée par OLSR.

Mots-clé : Réseau sans fil, réseaux mobile ad-hoc, inondation, multipoint relai, graphes aléatoires, séries génératrices.

1 Introduction

Radio networking is emerging as one of the most promising challenge of modern technology. Mobility gives the opportunity of a new dimension of freedom in Internet use. Among the numerous architectures that can be adapted to radio networks, the *Ad-hoc* topology is the most attractive one since it consists to connect mobile nodes without relying on pre-existing infrastructures. When some nodes are not directly in range of each other there is a need of packet relaying by intermediate nodes. The working group MANet of Internet Engineering Task Force (IETF) is standardizing routing protocol for *ad-hoc* wireless networking under Internet Protocol (IP). In MANet every node is a potential router for other nodes. The task of specifying a routing protocol for a mobile wireless network is not a trivial one. The main problem encountered in mobile networking is the limited bandwidth and the high rate of topological changes and link failure caused by node movement. In this case the classical routing protocol as Routing Internet Protocol (RIP [1]) and Open Shortest Path First (OSPF [2]) are not adapted since they need too much control traffic and can only accept few topology changes per minute.

MANet working group proposes two kinds of routing protocols:

1. The reactive protocols;
2. the pro-active protocols.

The reactive protocols such as Ad-hoc On Demand Distance Vector (AODV [13]), Direct Source Routing (DSR [3, 4]), Temporally-Ordered Routing Algorithm (TORA [10, 11]), do not need control exchange data in absence of data traffic. Route discovery procedure is invoked on demand when a source has a new connection pending toward a new destination. The route discovery procedure in general consists into the flooding of a *query* packet and the return of the route by the destination. The exhaustive flooding can be very expensive, thus creating delays in route establishment. Furthermore the route discovery via flooding does not guarantee to create optimal routes in terms of hop-distance.

The pro-active protocols such as Destination-Sequenced Distance-Vector Routing (DSDV [12]), Optimized Link State Routing (OLSR [6, 7]), AODV, needs periodic update with control packet and therefore generates an extra traffic which adds to the actual data traffic. The control traffic is broadcasted all over the network via optimized flooding. Optimized flooding is possible since nodes permanently monitor the topology of the network. OLSR uses multi-point relay flooding which very significantly reduce the cost of such broadcasts. Furthermore, the node have permanent dynamic database which make optimal routes immediately available on demand.

To compare reactive protocols and pro-active protocols needs to compare the overhead due to route discovery and route non-optimality with the overhead caused by periodic control traffic. This comparison can only be done in very precise network and traffic conditions. In this paper we apply the model of random graph to *ad-hoc* networking. The paper is divided in three parts. Section 2 describes the random graph model. Section 3 analyzes the performance of a reactive protocol (DSR) under the random graph model. Section 4 analyzes the performances of a pro-active protocol (OLSR) under the same model.

2 The random graph model

In the following we consider a mobile network made of n nodes. We assume the two following assumptions:

1. when several nodes are waiting for transmission only one node can transmit at a time and the transmitter node is randomly selected among the waiting nodes;

2. the events "a node A correctly receives the packets transmitted by node B" are i.i.d. when A and B vary in the graph and each event occur with fixed probability p.

The first assumption basically means that the transmission protocol is a CSMA-like protocol and that the range where a transmission can be detected covers the entire network. This is a reasonable extrapolated assumption since in usual signal attenuation model the radius within which a transmission can be detected is in general between two and three times the size of the radius within which the data contained in the transmission can be correctly received. This property is a consequence of the fact that in broadband wireless transmission, correct receptions need an important ratio of signal over noise (RSN). In other words, this model ignores spatial reuse.

The second assumption basically means that the graph of interconnection in the mobile network is a random graph where the validity of each link is an i.i.d event with probability p. This model is particularly relevant for mobile networks where nodes are virtually in range of each other but random perturbations make that some pair of nodes cannot receive each other. A straightforward example is with indoor ad-hoc networks and random obstacles (furniture, wall) randomly obstruct transmissions. Figure 1 shows an example of a random graph with $(n, p) = (10, 0.7)$, the nodes have been drawed in concentric mode just for convenience.

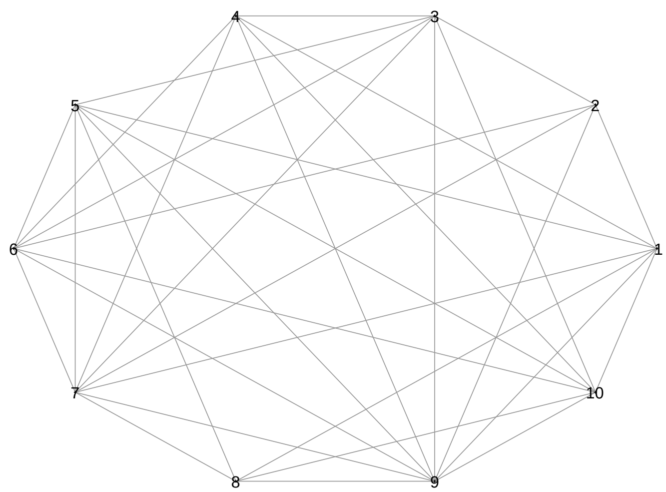

Figure 1: A random graph with $n = 10$ and $p = 0.7$, generated by Maple

When the network is located outdoor and span on a significant geographical area, the probability p should depend on the distance between the two nodes, in a function which basically should decrease with distance.

In the sequel we will particularly focus on dense networks: *i.e.* random graph whose size n tends to infinity with fixed p. In the sequel we also denote $q = 1 - p$.

3 Analysis of a reactive protocol

The reference protocol for reactive protocol is Distance Source Routing (DSR) protocol [3]. In most reactive protocols, routes discovery proceeds via flooding of a query packet from the source to the destination. Exhaustive flooding consists into all nodes retransmitting the packet. The packet is updated at each retransmission so that it contains the addresses of the nodes it has passed through. When the destination receives the query packet it returns to the source the path contained in the first packet received. The path is included in the further data packets which are routed via source routing procedure.

3.1 Average flooding distance

Since the destination returns the first path it receives from the query packet, there is no guarantee that the route is optimal. Furthermore the length of the route is a random variable when packet retransmission is random, which is the case in the random graph model. The average length of the route to a given destination is called the *average flooding distance*. Our aim is to find an estimate of the average flooding distance in the random graph model when the number of nodes n tends to infinity.

Since our model ignores spatial reuse, we can enumerate the query retransmission from 0 to $n-1$ according to their transmission order. The 0-th retransmission is in fact the first transmission of the query by the source nodes, and the $n-1$th transmission is the last one in the flooding protocol. There is no specific properties of the nodes that makes the transmissions, excepted that for any integer k, the node which makes the retransmission of order k must have beforehand received correctly the query from the k first transmitter.

We call d_k the average flooding distance of the node which made the retransmission of order k. We have clearly $d_0 = 0$ and $d_1 = 1$.

Theorem 1 *The average flooding distance between two random nodes in a random graph tends to* $\frac{p}{q}\sum_{k=1}^{\infty}\frac{q^k}{1-q^k}$*, when the size of the graph, n, tends to infinity.*

Proof: The probability that any given node receives for the first time the query at the ith retransmission $i < k$ is $(1-p)^i p$ and in this case its average flooding distance is $1 + d_i$. Since the node which makes the kth transmission has received the query at least once from the k first retransmission, we have to condition this probability by $(1 - q^k)$ to obtain the recursion

$$(1 - q^k) \times (d_k - 1) = \sum_{i=0}^{i=k-1} pq^i d_i \ . \tag{1}$$

If we introduce the generating function $D(z) = \sum_{k=0}^{\infty} d_k z^k$, the above recursion becomes

$$D(z) - D(qz) = \frac{1}{1-z} - \frac{1}{1-qz} + \frac{pz}{1-z} D(qz) \tag{2}$$

and

$$(1 - z)D(z) = \frac{pz}{1-qz} + (1 - qz)D(qz) \tag{3}$$

which resolves into

$$(1 - z)D(z) = \frac{p}{q} \sum_{k=1}^{\infty} \frac{q^k z}{1 - q^k z} \ . \tag{4}$$

The destination of the query receives its first copy from the ith transmission with probability $(1-p)^i p$ and in this case its average flooding distance is $1+d_i$. Therefore the unconditional flooding distance is $1 + pD(q)$ and the theorem holds.

Corollary 1 *Excluding control packets, the ratio between the maximum useful throughput and the nominal channel throughput with DSR in a random graph model is* $\left(\frac{p}{q} \sum_{k=1}^{\infty} \frac{q^k}{1-q^k}\right)^{-1}$. *With OLSR with optimal routes this ratio is* $(1 + q)^{-1}$.

Figure 2 displays the useful throughput attainable with respectively flooding routes (like with DSR protocol) and optimal routes (like with OLSR protocol).

Theorem 2 *When* $p \to 0$ *the average flooding distance is equivalent to* $\log \frac{1}{p}$

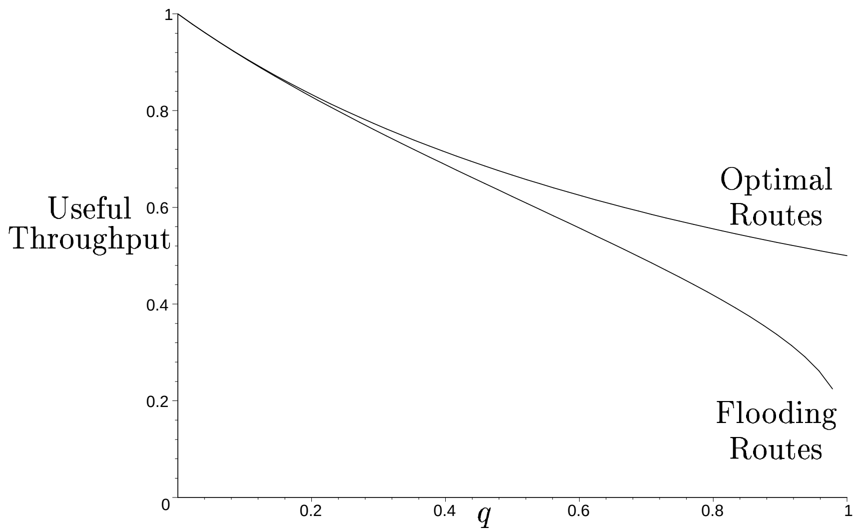

Figure 2: useful throughputs as a function of $q = 1 - p$ with flooding routes and optimal routes

Proof: The function $f(x) = \sum_{k=1}^{\infty} \frac{e^{-kx}}{1-e^{-kx}}$ has a Mellin transform $f^*(s) = \int_0^\infty f(x)x^{s-1}dx$ for $\Re(s) > 1$. Simple algebra gives:

$$f^*(s) = \zeta^2(s)\Gamma(s) \quad (5)$$

where $\zeta(s) = \sum_{k=1}^{\infty} k^{-s}$, the celebrated *zeta* function of Riemann and $\Gamma(s)$ the Euler *gamma* function. Function $f^*(s)$ has a singularity at $s = 1$ which is a double pole: $f^*(s) = \frac{1}{(s-1)^2} + O(\frac{1}{1-s})$. By virtue of the reverse Mellin transform [14], one obtain the asymptotic expansion $f(x) = \frac{-\log x}{x} + O(\frac{1}{x}$ which proves the theorem.

We can develop further the distribution of the flooding distance (second moment, etc). To this end, let P^k denote the probability that the flooding distance of a random point is equal to k. We introduce $P(u)$ to denote the *probability generating function* (p.g.f.) of the flooding distance:

$$P(u) = \sum_k P^k u^k \ . \quad (6)$$

Theorem 3 *The p.g.f. $P(u)$ of the flooding distance between two random nodes in a random graph, when n tends to infinity, tends to $up\prod_{k=1}^{\infty} \frac{1-(1-up)q^k}{1-q^k}$.*

Proof: Let $P_k(u)$ be the p.g.f. of the flooding distance to the source of the k-th transmitter in the chain. We have $P_0(u) = 1$ and $P_1(u) = u$. We have the recursion

$$(1 - q^k)P_k(u) = u \sum_{i=0}^{i=k-1} pq^i P_i(u) \ , \tag{7}$$

which is equivalent to the functional equation, with $P(z,u) = \sum_{k=0}^{\infty} P_k(u) z^k$:

$$P(z,u) - P(qz,u) = \frac{up}{1-z} P(qz,u) \ . \tag{8}$$

The above equation is easy to resolve:

$$(1-z)P(z,u) = (1-(1-up)z) \prod_{k=1}^{\infty} \frac{1-(1-up)q^k z}{1-q^k z} \ . \tag{9}$$

The destination would receives the query for the first time from the k-th transmitter in the chain with probability pq^k and will add one to the flooding distance of this transmitter to the source. Therefore the p.g.f. of the flooding distance conditioned by the fact that the destination receives the query from the k-th transmitter is $uP_k(u)$. The unconditional p.g.f of the flooding distance is therefore $\sum_{k=0}^{\infty} pq^k uP_k(u)$ which is equal to $upP(q,u)$, which ends the proof of the theorem.

Figure 3 displays the distribution of the flooding distance with respect to $q = 1 - p$.

3.2 Asymmetric routes

In most Medium Access Control, there is an acknowledgment at each hop for unicast packet. Therefore there is a need that the route to the source and destination be exclusively made of symmetric links. Unfortunately most flooding are done with broadcast packet and are not hop by hop acknowledged. Therefore the flooding process does not check the symmetry of any link, and there is a non zero probability that the route returned by the destination contains an assymetric links and therefore is not a valid route.

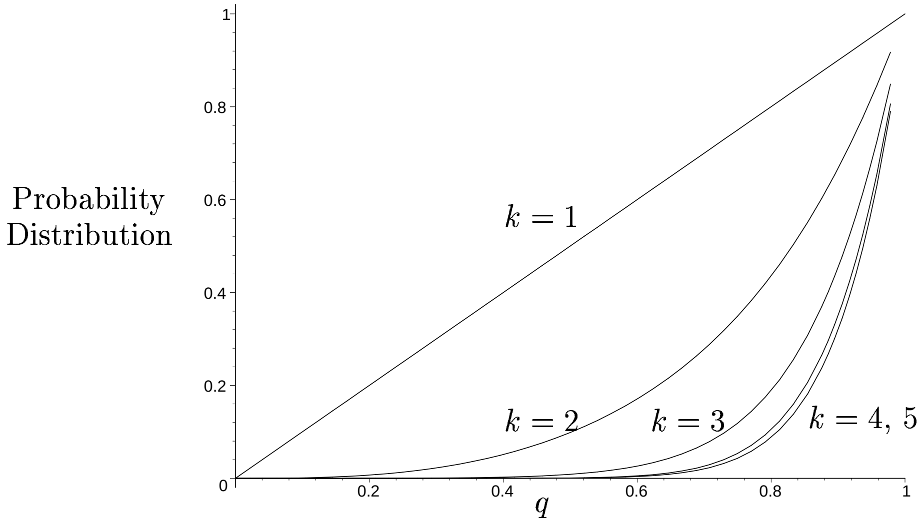

Figure 3: Probability that the flooding distance is greater than k in q

The impact of an assymetric route may depend on how the routing protocol returns the route to the source. If the route is returned via a different path, there is no way for the source to detect asymmetric links other than via failure report during data transmission. In some reactive protocol such as DSR, the route is returned to the source in unicast packet sent on the reversed route. In this case the asymmetry of the link is simply detected by the failure of the return packet. DSR specifies a timeout which doubles after each route return failure and cancels after 16 consecutive failures. In this case it is crucial that the probability that the flooding route be asymmetric be well under $1/2$ otherwise the DSR route-timeout process would diverge.[1]

Our aim is to derive the probability that a flooding route contains an asymmetric link given the following assumption:

- Each link let pass the query packet with probability p as in the random graph model;

[1]In fact in DSR, the destination should return a route for every received copy of the query which augment the probability of sending a symmetric route; but there are architecture where only the first route is returned, for example when the destination is linked tot he network via a single link.

- The links which had let pass the query packet have independent probability ρ to be symmetric.

Theorem 4 *The probability that a flooding route is symmetric in the random graph model, when n tends infinity, is* $\pi(p,\rho) = \rho p \prod_{k=1}^{\infty} \frac{1-(1-\rho p)q^k}{1-q^k}$.

Proof: Let π_k be the probability that the kth re-transmitter of the query has a symmetric flooding route to the source. We have $\pi_0 = 1$ and $\pi_1 = \rho$. Paraphrasing the analysis done in the previous subsection we have the recursion:

$$(1-q^k)\pi_k = \rho \sum_{i=0}^{i=k-1} pq^i \pi_i \ , \tag{10}$$

which translate to the functional equation, with $P(z) = \sum_{k=0}^{\infty} \pi_k z^k$:

$$P(z) - P(qz) = \frac{\rho p}{1-z} P(qz) \ . \tag{11}$$

The above equation straightforwardly resolves into

$$(1-z)P(z) = (1-(1-\rho p)z) \prod_{k=1}^{\infty} \frac{1-(1-\rho p)q^k z}{1-q^k z} \ . \tag{12}$$

The destination receives the query for the first time from its ith re-transmitter with probability pq^i and the link to this re-transmitter is symmetric with probability ρ, and the flooding route to the ith re-transmitter is symmetric with probability π_i. Therefore the unconditional probability that the flooding route to the destination is symmetric is $\rho p P(q)$ which ends the proof of the theorem.

Figure 4 displays a 3D plot of the probability $\pi(p,\rho)$ for a symmetric flooding route with respect to variable $q = 1-p$ and ρ.

With DSR protocol the time period between two route discovery attempts starts with value T and doubles after each failure, and it does so until it reaches a value $T_{\max}$ and after this event the period is remains at this value. Only 16 attempt are permitted by DSR to discover the route to a given destination. We assume that at each attempt the flooding route is asymmetric with independent probability $1-\pi(p,\rho)$ and in this case cannot be returned with the source which has to make a further route discovery attempt.

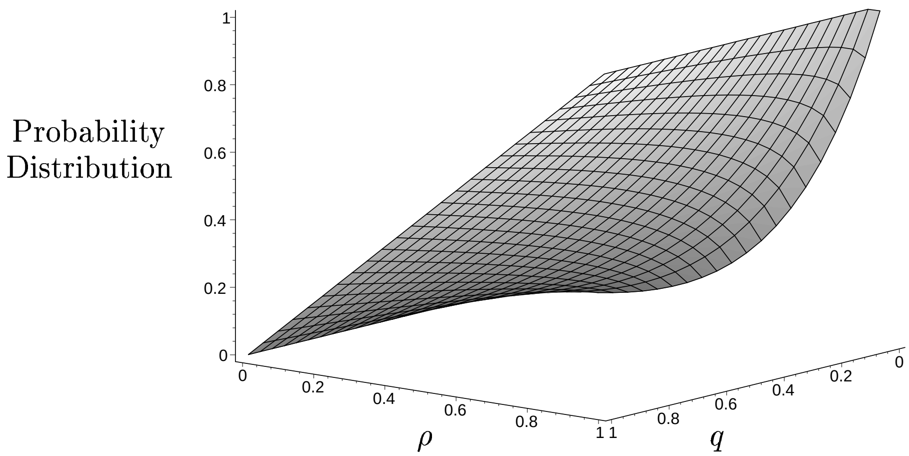

Figure 4: Probability of symmetric flooding route in (q, ρ)

Corollary 2 *The average time needed for a DSR node to find a valid route is equal to*

$$T_{\max} \times \left((1-\pi(p,\rho))^{i_{\max}} - (1-\pi(p,\rho))^{16}\right)(\pi(p,\rho))^{-1} + T\sum_{i=0}^{i_{\max}} 2^i(1-\pi(p,\rho))^i \ , \tag{13}$$

where T is the timeout for the first route failure report, $T_{\max}$ the largest acceptable timeout and $i_{\max}$ the largest integer i such that $2^iT < T_{\max}$.

Figure 5 displays the average time needed for DSR protocol to find a valid route with asymmetric links. The value of T is 0.5 second, and $T_{\max}$ is 10 second.

4 Analysis of a pro-active protocol

We will mainly focus our analysis over Optimized Link State Routing algorithm (OLSR) [7], but our first considerations about route optimality will be general.

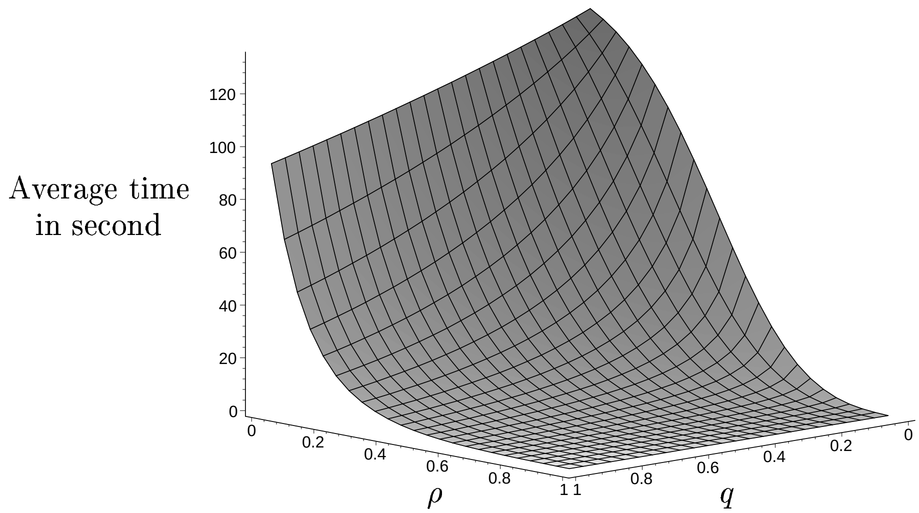

Figure 5: average time for DSR for route discovery with asymmetric links in (q, ρ)

4.1 Route optimality

Most pro-active protocols (like OLSR) have the advantage to deliver optimal routes (in term of hop number) to data transfers. The analysis of optimal routes is very easy in random graph models since a random graph tends to be of diameter 2 when n tends to infinity with fixed p.

Theorem 5 *The optimal route between two random nodes in a random graph, when n tends to infinity,*

(i) is of length 1 with probability p;

(ii) or of length 2 with probability $1 - p$.

Proof: Point (i) is an easy consequence of the random graph model. For point (ii) we consider two nodes, node A and node B, which are not at distance 1 (which occurs with probability $1-p$). We assume *a contrario* that these nodes are not at distance 2, and we will prove that would occur with a probability p_3 which exponentially tends to zero when n increases. If the distance between A and B is greater than 2, then for each of the $n-2$ remaining nodes in the network either

1. the link to A is not valid;

2. or the link to B is not valid.

For every remaining node the above event occurs with probability $1 - p^2$, therefore $p_3 = (1 - p^2)^{n-2}$, which proves the theorem.

4.2 Multi-point relay flooding

OLSR is the IP level 3 version of the level 2 intra-forwarding protocol of HIPERLAN [5, 6] which is the European HIgh PErformance Radio LAN normalized for operating at 5.2 GHz with nominal capacity of 23 Mbps on each of its five channels. Like HIPERLAN OLSR uses multi-point relays for improving flooding and broadcast transmission. The multi-point relays improves routing performance in two aspects:

1. it significantly reduces the number of retransmissions in a flooding or broadcast procedure;

2. it reduces the size of the control packets since OLSR nodes only broadcast its multi-point relay list instead of its whole neighborhood list in a plain link state routing algorithm.

We will focus on both points in the sequel of this section. First we remind a definition of the multi-point relay set of a given node A in the graph. We define the neighborhood of A as the set of nodes which have a valid link to A. We define the two-hop neighborhood of A as the set of nodes which have an invalid link to A but have a valid link to the neighborhood of A. The multi-point relay set of A (MPR(A)) is an arbitrary subset of the neighborhood of A which satisfies the following condition: every node in the two-hop neighborhood of A must have a valid link toward MPR(A).

The smaller is the Multi-point Relay set is, the more optimal is the routing protocol. [8] gives an analysis and examples about multi-point relay search algorithms. The use of the multi-point relays is in broadcast and flooding retransmission :

> *A node retransmits a broadcast packet only if has received its first copy from a node for which it is a multi-point relay.*

[6] gives a proof that such selective flooding protocol (multi-point relay flooding) eventually reach all destinations in the graph. [6] gives also the proof that the route obtained by OLSR by using multi-point relay points are optimal. As in HIPERLAN, an OLSR router computes the route to an arbitrary destination by using its local topological database made of its neighbor list and the multi-point relay sets of every remote nodes. The neighbor list is obtained from neighbor sensing and the multi-point sets are obtained by TC control packet reception.

Theorem 6 *For all $\varepsilon > 0$, the optimal multi-point point relay set of any arbitrary node is smaller than $(1+\varepsilon)\frac{\log n}{-\log q}$ with probability tending to 1 when n tends to infinity.*

Proof: We assume that a given node A randomly selects k nodes in its neighborhood and we will fix the appropriate value of k which makes this random set a valid multi-point relay set. The probability that any given other point in the graph be not connected to these randomly selected k multi-point relays is $(1-p)^k$. Therefore the probability that there exists a point in the graph which is not connected via a valid link to the random set is smaller than $n(1-p)^k$. Taking $k = (1+\varepsilon)\frac{\log n}{-\log q}$ for some $\varepsilon > 0$ makes the probability tending to 0.

Figure 6 displays the average size of the multi-point relay set of an arbitrary node as a function of n between 1 and 100, and $q = 1 - p$

Corollary 3 *A control packet with OLSR in random graph model contains a neighbor address list of length smaller than $(1+\varepsilon)\frac{\log n}{-\log q}$ with probability tending to 1, when n increases.*

This size very favorably compares to the average size of the whole neighborhood of the node which is pn. Notice that non-optimized link state algorithms must periodically broadcast their neighbor list.

Theorem 7 *The broadcast or flooding via multi-point relays takes in average a number of retransmission smaller than $(1+\varepsilon)\frac{\log n}{-p\log q}$.*

Proof: First we notice that this average number favorably compare to the unrestricted flooding needed in plain links state routing algorithms and with reactive protocols which needs exactly n retransmissions per flooding.

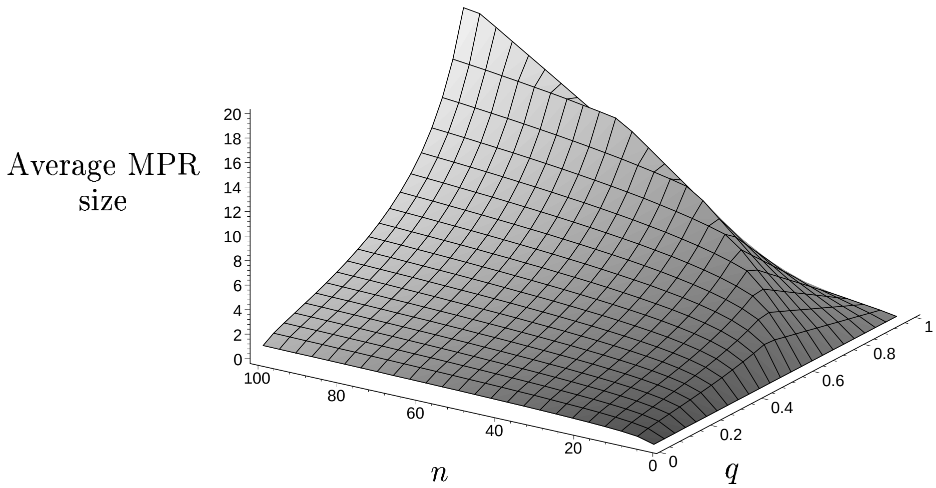

Figure 6: average multi-point relay set size in (p, n)

We index the retransmission according to their chronological order. The 0-th retransmission corresponds to the source of the broadcast. We call m_k the size of the multi-point relay set of the k-th re-transmitter. We assume that each of the m_k multi-point node of the kth transmitter are chosen randomly as in the proof of theorem 6. The probability that a given multi-point relay points of the k-th transmitter which did not receive a copy of the broadcast packet from the k first retransmission is $(1-p)^k$. Therefore the average number of new multi-point relays which will have to retransmit the broadcast packet after its kth retransmission is $(1-p)^k m_k$. Consequently the average total number of retransmissions does not exceeds $\sum_{k\geq 0}(1-p)^k m_k$.

Using the upper bound $m_k \leq (1+\varepsilon)\frac{\log n}{-\log q}$, the average number of retransmission is upper bounded by $(1+\varepsilon)\frac{\log n}{-\log q}\sum_{k\geq 0}(1-p)^k = (1+\varepsilon)\frac{\log n}{-p\log q}$, which end the proof of the theorem.

Figure 7 displays the average number of packet retransmission in a multi-point relay flooding as a function of p between 0 and 1 and n between 1 and 1000. Figure 8 displays the average number of retransmissions in a multi-point relay flooding when $n = 1000$ and p varies between 0 and 1. Figure 9 displays the average number of retransmissions in a multi-point relay flooding when n

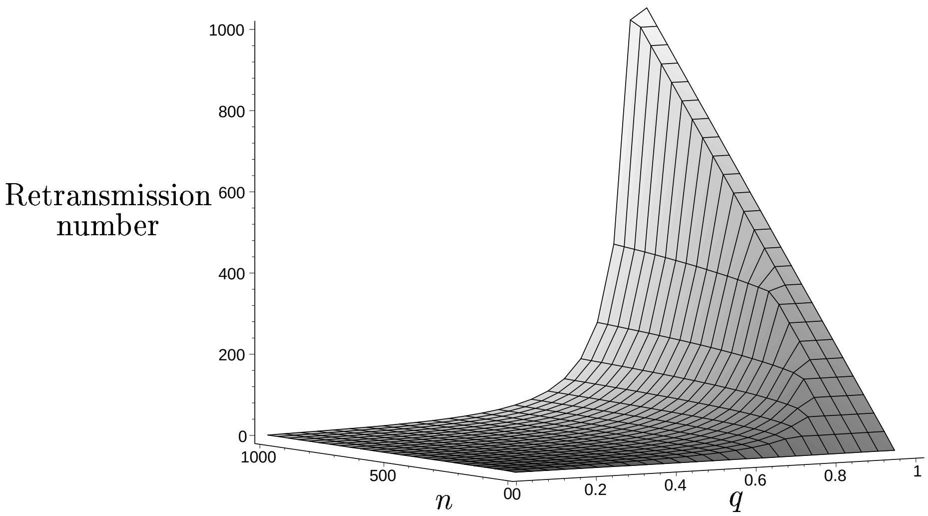

Figure 7: average number of retransmissions in a multi-point relay flooding in (q, n)

varies between 1 and 1000 and p fixed at value 0.9. In both figures, comparison is made with the number of retransmissions in exhaustive flooding as it is done in OSPF and DSR.

The nodes inform the other nodes about its multi-point relay set by broadcasting the list of its multi-point relays in TC packets. The broadcast of TC packets also uses multi-point relays, therefore it is possible to estimate the average traffic created by those control packets.

Corollary 4 *The cost of OLSR control traffic in random graph model is $O(n(\log n)^2)$ compared to $O(n^3)$ with plain link state algorithm.*

Remark: the control traffic does not include the neighborhood sensing needed to detect symmetric links and to let nodes locally building their their multi-point sets.

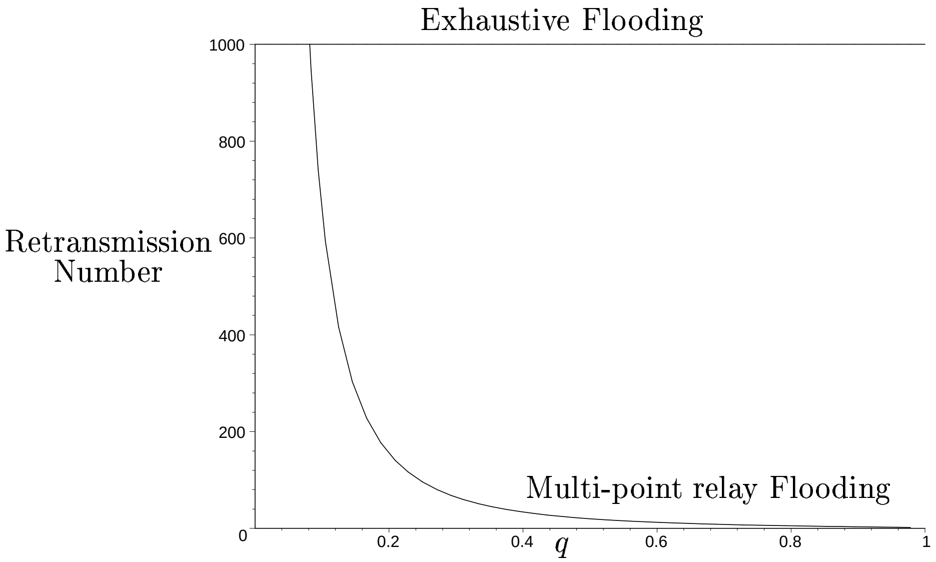

Figure 8: average number of retransmissions in multi-point relay flooding with $n = 1000$ and p variable

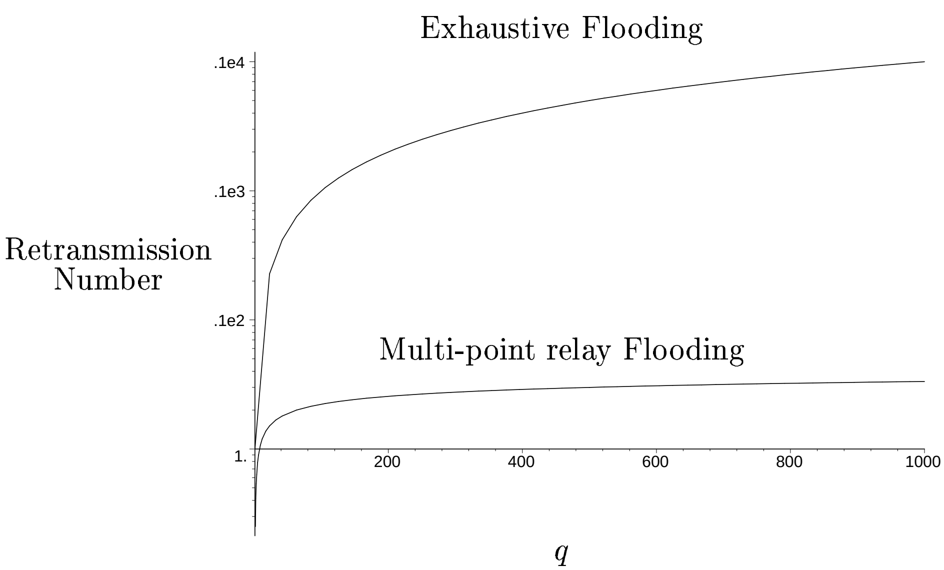

Figure 9: average number of retransmissions in multi-point relay flooding with n variable and $p = 0.9$, logarithmic scale.

5 Conclusion and further works

We have presented a performance evaluation of mobile ad-hoc routing protocols in the random graph model. We have analyzed a reactive protocol, DSR, and a pro-active protocol, OLSR. The results obtained provide significant insights in the performances of the protocols, in particular about the impact of route non-optimality and/or asymmetry in reactive protocols, the potential of flooding optimization in pro-active protocols. The originality of the present performance evaluation is that it is completely based on analytical methods (generating function, asymptotic expansion) and does not rely on simulation software. The random graph model is enough realistic for indoor or short range outdoor networks where link fading mainly comes from random obstacles. Nevertheless the random graph model is not well adapted for extended outdoor networks where link fading mainly comes from distance attenuation. In this case the random graph model can be improved by letting the parameter p depending on distance x between the nodes as in [9]. The analytical derivation of the performances of the routing protocol in the distance dependent random graph will be subject of further works.

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