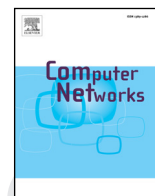




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Impact of noise and interference on probabilistic broadcast schemes in mobile ad-hoc networks

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ABSTRACT

Broadcasting is a vital part of on-demand routing protocols to discover new routes in mobile ad-hoc networks (MANET). Pure flooding is the earliest and still widely used mechanism of broadcasting for route discovery in on-demand routing protocol. In pure flooding, a source node broadcasts a route request to its neighbors. These neighbors then rebroadcast the received route request to their neighbors until the route request arrives at the destination node. Pure flooding may generate excessive redundant traffic leading to increased contention and collisions deteriorating the performance. To limit the redundant traffic, a number of probabilistic broadcast schemes have been proposed in the literature. However, the performance of those probabilistic broadcasting schemes is questionable under real life MANETs which are noisy in nature. Environmental factors like thermal noise and co-channel interference may have adverse effects on the system performance. This paper investigates the effects of thermal noise and co-channel interference on the performance of probabilistic schemes employed in the route discovery mechanism in MANETs. Based on extensive ns-2 simulations, this paper discovers that, contrary to the findings of previous studies, these schemes do not outperform pure flooding scheme when thermal noise and co-channel interference are taken into account.

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1. Introduction

A mobile ad-hoc network (MANET) consists of a set of mobile nodes that can connect to each other over multi-hop wireless links on ad-hoc basis. These networks are self-organizing, self-configuring as well as self-healing without requiring any infrastructure or central administration [1–4]. These properties make a MANET an excellent candidate for a number of applications ranging from communication in battle fields to rescue operations in disaster areas.

MANET nodes can arbitrarily be located within an area and are free to move. The movement of MANET nodes changes the network topology dynamically. MANET nodes

adapt to the changing topology by discovering new neighbors and establishing new routes to destinations [5].

Due to the limited transmission range, a node may not communicate directly with a distant node and may have to rely on its neighboring nodes to relay the message along the route to the final destination node. Therefore, each node acts not only as a host node but also as a relay node to extend the reachability of other nodes. When a node needs to send data to a remote node, first, it finds out a set of relay nodes between itself and the remote node. The process of finding the optimal set of relay nodes between the source node and the destination node is called routing. Node mobility, limited battery power and the error-prone nature of wireless links are the main challenges in designing an efficient routing protocol in MANETs.

A number of routing protocols have been proposed in the literature [6]. These protocols generally fall into three categories namely table-driven (proactive), on-demand (reactive) and hybrid routing protocols. Table-driven routing protocols

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32 aim to maintain routes to all possible destinations in the net-
 33 work at all times. Examples of table-driven routing protocols
 34 include OLSR (Optimized Link State Routing) [7] and DSDV
 35 (Destination-Sequenced Distance-Vector) routing [8]. In con-
 36 trast to table-driven approach, on-demand routing protocols,
 37 e.g., AODV (Ad-hoc On-demand Distance Vector) routing [9],
 38 DSR (Dynamic Source Routing) [6], and ABR (Associativity-
 39 Based Routing) [10], discover a route only when it is needed.
 40 Hybrid routing protocols, e.g., ZRP (Zone Routing Protocol)
 41 [11] and CEDAR (Core-Extraction Distributed Ad-hoc Rout-
 42 ing) [12] combine the features of both proactive and reactive
 43 routing protocols.

44 In on-demand routing protocols, the routing process
 45 consists of two phases namely route-discovery and route-
 46 maintenance. These protocols rely on broadcasting for route
 47 discovery. For example, in case of AODV routing protocol, a
 48 source node that needs to send data to a destination node
 49 triggers route discovery mechanism by broadcasting a spe-
 50 cial control packet called Route Request (RREQ) to its neigh-
 51 bors who then rebroadcast the RREQ packet to their neigh-
 52 bors. The process continues until the RREQ packet arrives at
 53 the destination node. The destination node sends a control
 54 packet called Route Reply (RREP) that follows the path of
 55 RREQ in reverse direction and informs the source node that
 56 a route has been established. Since every node on receiving
 57 the RREQ for the first time rebroadcasts it, it requires $N-2$ re-
 58 broadcasts in a network of N nodes assuming the destination
 59 is reachable. This kind of broadcasting is called pure flooding
 60 and is depicted briefly in Fig. 1 while details can be found in
 61 [13].

62 Pure flooding often results in substantial redundant trans-
 63 missions because a node may receive the same packet from
 64 multiple other nodes. This phenomenon, commonly known
 65 as the broadcast storm problem (BSP) [14], triggers frequent
 66 contention and packet collisions leading to increased com-
 67 munication overhead and serious performance complica-
 68 tions in densely populated networks. The broadcast storm
 69 problem equally affects the route maintenance phase dur-
 70 ing which routes are refreshed by triggering new route dis-
 71 covery requests to replace the broken routes. To elevate the
 72 damaging impact of pure flooding, a number of improved
 73 broadcasting schemes have been proposed in the literature
 74 [14–16]. These techniques generally fall in two categories
 75 namely deterministic and probabilistic broadcasting. Deter-
 76 ministic schemes (e.g., MPR [17] and Self Pruning Scheme
 77 [18]) exploit network information to make more informed
 78 decisions. However, these schemes carry extra overhead to

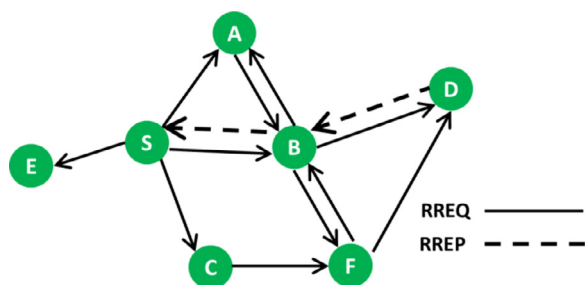


Fig. 1. Route discovery mechanism in AODV.

79 exchange location and neighborhood information among
 80 nodes. On the other hand, the probabilistic schemes, e.g.,
 81 fixed-probabilistic [19], distance-based [20], counter-based
 82 [21] and location-based [14] schemes, take a local decision to
 83 broadcast or not to broadcast a message according to a prede-
 84 termined probability. All these schemes try to minimize the
 85 number of rebroadcasted RREQ packets. In fixed-probabilistic
 86 scheme, a node receiving the RREQ packet rebroadcasts it
 87 with a fixed probability. In case of distance-based scheme,
 88 a node receiving the RREQ packets decides to rebroadcast by
 89 considering its distance from the sending node.

90 Real life MANETs are noisy and the communication
 91 is not error free. A number of channel impairments like
 92 noise, co-channel interference, signal attenuation, fading and
 93 user mobility affect the transmission. Previous studies have
 94 shown that routing protocols based on probabilistic broad-
 95 cast schemes outperform the traditional pure flooding based
 96 routing protocols [14,22]. However, the results of those stud-
 97 ies can be challenged for real MANETs. It is because those
 98 studies either ignored the noise and the interference at all
 99 [16,23] or they used a simplified model by translating the ef-
 100 fects of noise and interference into a simple packet loss prob-
 101 ability [24].

102 This paper investigates the effects of thermal noise and
 103 co-channel interference on the performance of probabilistic
 104 schemes by using realistic models of thermal noise and co-
 105 channel interference at physical and MAC layers. The investi-
 106 gations have been carried out for the fixed-probabilistic [19]
 107 and the distance-based [20] broadcast schemes. The perfor-
 108 mance is evaluated by considering routing overhead, appli-
 109 cation layer throughput, end-to-end delay and energy con-
 110 sumption. Through extensive ns-2 simulations and analy-
 111 sis of the simulation results, this paper reveals that, in con-
 112 trast to the previous studies, the fixed-probabilistic and the
 113 distance-based broadcasting schemes do not show promis-
 114 ing results when realistic thermal noise and co-channel in-
 115 terference at the physical and the MAC layers are taken
 116 into account. The rest of the paper is organized as follows.
 117 Section 2 highlights the related work. Section 3 presents the
 118 simulation setup, performance evaluation and discussion of
 119 results followed by conclusion in Section 4.

120 2. Related work

121 Cartigny and Simplot [26] proposed a probabilistic
 122 scheme where the retransmission probability is calculated
 123 from the number of neighboring nodes which are consider-
 124 ing rebroadcasting. This work showed that a fixed param-
 125 eter could be derived to enhance the reachability and demon-
 126 strated a substantial reduction in broadcast traffic yielding
 127 encouraging results. However, this work did not consider the
 128 effects of interference and thermal noise.

129 Zhang and Agrawal [22] suggested a probabilistic scheme
 130 that dynamically modifies the rebroadcasting probability
 131 based on the node distribution and the node movement
 132 by considering local information but without needing any
 133 distance measurements or exact location determination de-
 134 vices. Their results showed an improvement in performance
 135 when compared to both pure flooding and static probabilistic
 136 schemes. However, the effects of noise and interference were
 137 ignored. The same authors (in another work [27]) suggested

138 a leveled probabilistic routing scheme for MANETs. In this
139 scheme, mobile hosts are divided into four groups and dif-
140 ferent rebroadcast probabilities are assigned to each group.
141 The results showed gains in throughput.

142 Al-Bahadili and Sabri [24] proposed a probabilistic algo-
143 rithm for route discovery based on the noise-level. However,
144 this work used a model to estimate interference and noise
145 values rather than measuring them at lower layers and pass-
146 ing it to the network layer.

147 Ruiz and Bouvery [23] proposed a cross layer design for
148 enhancing the distance based broadcasting protocol in terms
149 of energy consumption. They enhanced it by minimizing the
150 transmission power of candidate node uses for the broad-
151 casting process in order to reduce the number of collisions
152 and save energy. Their results have shown that there was re-
153 duction in the number of collisions in the network and en-
154 ergy consumption. The gain increased with increase of net-
155 work density. However, this work did not consider the effects
156 of interference and thermal noise.

157 To the best of the authors' knowledge, no previous work
158 on probabilistic route discovery mechanism has considered
159 the effect of physical layer parameter such as thermal noise
160 and co-channel interference. To remark conclusively about
161 any probabilistic route discovery scheme if it is recom-
162 mended approach or not for on-demand routing protocol in
163 real life MANETs, the effect of interference and thermal noise
164 has to be taken into account. This paper fills this gap and
165 studies the effects of interference and thermal noise on the
166 performance of a probabilistic route discovery scheme. In
167 this paper, the signal strength, noise level and interference
168 are measured at the physical and MAC layer and the result-
169 ing signal to interference plus noise ratio (SINR) is used to
170 determine the successful reception of packets. SINR is a com-
171 mon way to represent a wireless channel and has been ex-
172 tensively used to measure the performance of wireless links
173 [28]. Abrate et al. [29] presented a novel model to show the
174 relationship of Packet Error Rate (PER) and SINR for different
175 packet length.

176 Takai et al. [30] studied the role of physical layer model-
177 ing in evaluating the performance for higher layer protocols
178 and their results revealed that the physical layer modeling is
179 important even though the higher layer protocols do not in-
180 teract with the physical layer directly.

181 Alnajjar and Chen [31] stated a cross-layer mechanism
182 wherein the routing protocols adapt to the current Signal to
183 Noise Ratio (SNR). This approach was implemented in DSR
184 protocol and was shown to enhance the performance.

185 Linfoot et al. [32] studied the effects of physical and vir-
186 tual carrier sensing on the AODV routing protocol. This work
187 showed that the route discovery mechanism is affected by
188 the interference and carrier sensing range and a suitable car-
189 rier sensing threshold is crucial for performance gains in
190 noisy MANETs with high node density.

191 3. Performance evaluation of probabilistic broadcast

192 This section studies the impact of thermal noise and
193 co-channel interference on the performance of the fixed-
194 probabilistic [19] and the distance-based [20] broadcasting
195 schemes employed in the route discovery process of AODV
196 routing protocol in MANETs. The performance has been

197 evaluated using four metrics namely routing overhead,
198 throughput, end-to-end delay and energy consumption. The
199 performance evaluation has been carried out both with and
200 without taking the thermal noise and co-channel interfer-
201 ence into account. The reported results are supported by
202 network layer measurements of the number of RREQs pack-
203 ets broadcasted, received and rebroadcasted by all nodes.

204 3.1. Simulation setup

205 We used the ns-2 simulator (2.35v) [33] to analyze the
206 performance of the fixed-probabilistic and the distance-
207 based broadcasting schemes under realistic thermal noise
208 and co-channel interference in noisy MANETs. AODV is the
209 most widely used on-demand routing protocol [9,34] and it
210 uses pure flooding as its broadcasting mechanism for route
211 discovery. We modified the standard AODV routing pro-
212 tocol to AODV-P and AODV-D by incorporating the fixed-
213 probabilistic and the distance-based broadcasting schemes
214 respectively. Here P in AODV-P denotes the rebroadcast prob-
215 ability while D in AODV-D denotes the distance threshold. A
216 rebroadcasting node estimates its distance d from the send-
217 ing node by using the signal strength of the received RREQ
218 packet. The simulation parameters generally follow [24,35].
219 The network bandwidth is set to 6 Mbps and the medium
220 access control (MAC) protocol is simulated using the ns2
221 library dei80211mr [36]. This library calculates the PER using
222 pre-determined curves (PER Vs. SINR) for a given packet size.
223 Fig. 2 shows the PER Vs. SINR curve [36] used in our simula-
224 tions. The SINR value is computed from the received signal
225 strength, thermal noise and co-channel interference. Ther-
226 mal noise is set to -95 dBm following the recommendation
227 in [37].

228 The scenario consists of a fixed number of MANET nodes
229 placed randomly in an area of $1000 \times 1000 \text{ m}^2$. MANET
230 nodes move according to the Random Waypoint mobility
231 model [38] with a maximum speed of 10 m/s and the pause
232 time set to zero. To consider the effects on the application
233 layer, FTP (File Transfer Protocol) agents are attached to
234 nodes such that node i is downloading a file of infinite size
235 from node $i + N/2$ for $i = 1, 2, \dots, N/2$ where $N = 100$ is the
236 total number of nodes. For energy consumption analysis,

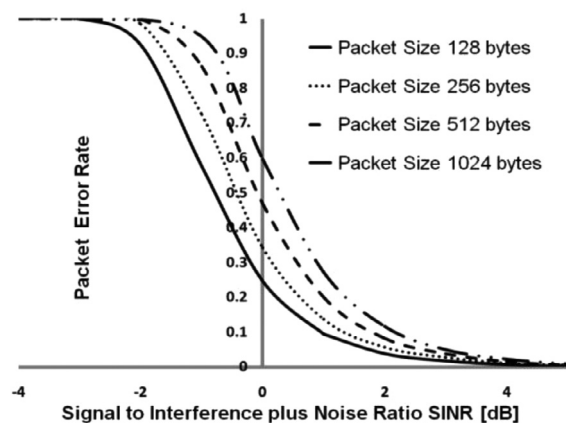


Fig. 2. Relationship between PER and SINR for different packet sizes [36].

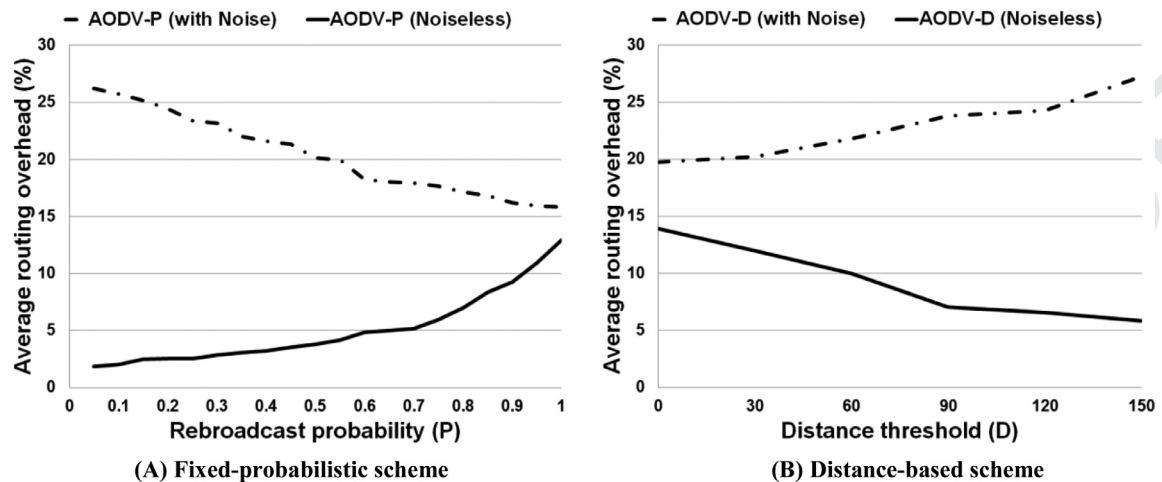


Fig. 3. Average routing overhead versus (A) rebroadcast probabilities, (B) distance threshold.

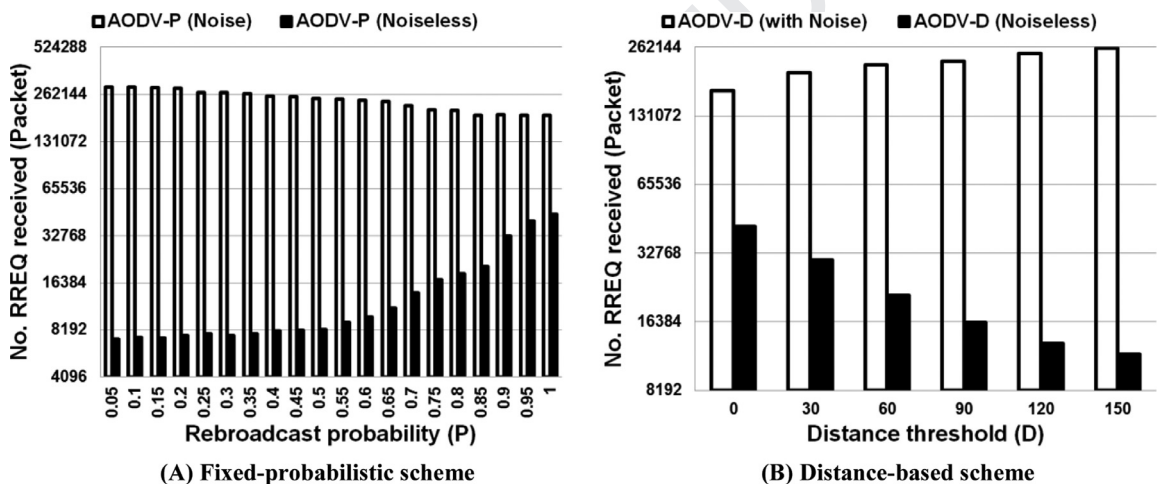


Fig. 4. Number of RREQ received versus (A) rebroadcast probabilities, (B) distance threshold.

237 each node has initial energy of 1000 J. Transmission power,
238 path loss and received power threshold are set such that the
239 effective transmission range is 250 m.

240 3.2. Simulation results and analysis

241 Simulation results are obtained by averaging the results
242 of 30 runs, each using a different seed value and lasting for
243 800 s. The seed value is used to set the initial location of
244 MANET nodes within the area. The aforementioned perfor-
245 mance metrics (routing overhead, throughput, end-to-end
246 delay and energy consumption) were measured for varying
247 the value of rebroadcast probability P for the AODV-P scheme
248 and by varying the distance threshold D for AODV-D scheme
249 with and without thermal noise and co-channel interference.
250 In the discussion below, term noise will be used to refer to
251 thermal noise and co-channel interference.

252 3.2.1. Routing overhead

253 Routing overhead is defined as the number of rout-
254 ing packets (control packets) transmitted per data packet

255 received. Fig. 3 depicts the average routing overhead for
256 both AODV-P and AODV-D schemes in noisy and noiseless
257 MANETs. It can be seen that for the noiseless case, the aver-
258 age routing overhead increases with P (in case of AODV-P)
259 and it decreases with D (in case of AODV-D). This relation-
260 ship is reversed when noise is taken into account for both
261 AODV-P and AODV-D schemes. This can be explained by explor-
262 ing the routing traffic. Let's consider the noiseless case first.
263 By increasing the value of P or decreasing the value of
264 D , the number of RREQs rebroadcasted and hence the number
265 of RREQs received both increase (see Figs. 4 and 6). This
266 increases the reachability of RREQs maximizing the chances
267 of finding a valid route in the first attempt. That's why the
268 total number of route requests, as denoted by the number of
269 RREQ packets broadcasted, initiated by all nodes decreases
270 by increasing the value of P or by decreasing value of D (see
271 Fig. 5). However, the downside is that many nodes receive
272 multiple copies of the same RREQ from different neighbors.
273 The redundant RREQ traffic increases with increasing the
274 value of P or by decreasing the value of D leading to higher
275 routing overhead.

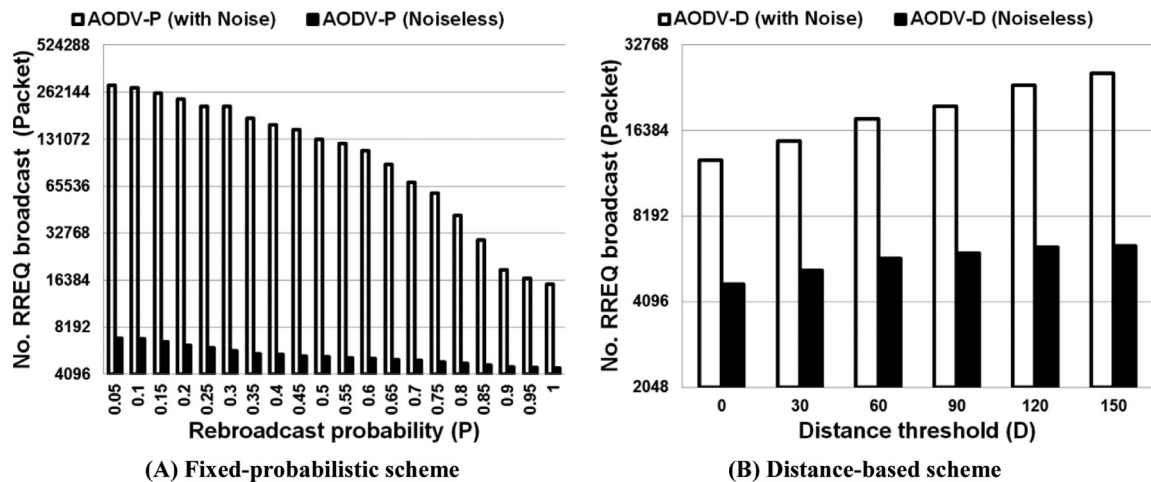


Fig. 5. Number of RREQ broadcast versus (A) rebroadcast probabilities, (B) distance threshold.

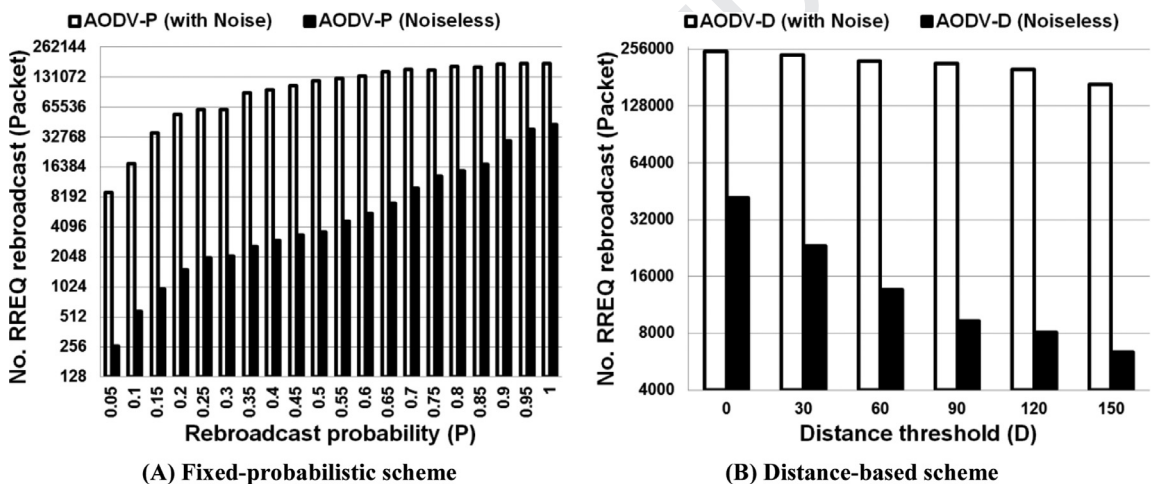


Fig. 6. Number of RREQ rebroadcast versus (A) rebroadcast probabilities, (B) distance threshold.

276 Now let's consider the noisy case. Both thermal noise and
 277 co-channel interference cause bit errors leading to packet
 278 losses. Thermal noise is independent of the traffic while co-
 279 channel interference increases with the traffic intensity. In-
 280 creasing the value of P or decreasing the value of D may in-
 281 crease the reachability of RREQs on one hand but it increases
 282 the co-channel interference, on other hand, leading to higher
 283 packet loss rate. This can be confirmed by observing that with
 284 increasing value of P or decreasing value of D , the number of
 285 rebroadcasted RREQs increases but the number of received
 286 RREQs decreases due to higher packet loss rate (see Figs. 4
 287 and 6). The fewer received RREQs limit the number of re-
 288 broadcasted RREQs as well. This explains why the number
 289 of rebroadcast packets increases with P at a lower rate for
 290 the noisy case compared to the noiseless case (see Fig. 6). In
 291 fact, thermal noise and co-channel interference act as natu-
 292 ral limiters for the traffic; the former is static while the latter
 293 is adaptive because it increases with traffic intensity. This re-
 294 duces the chances of getting duplicate RREQs from the neigh-
 295 boring nodes and adapts to the traffic intensity very well. In
 296 presence of natural and adaptive limiters (thermal noise and
 297 co-channel interference), the artificial limiters (reducing the

298 rebroadcast probability or rebroadcasting only from distant
 299 nodes) do not work well because it limits the reachability of
 300 RREQs independent of the traffic intensity and channel con-
 301 ditions. Nodes have to try several times before they get a valid
 302 route which increases the routing overhead.

3.2.2. Average throughput

303 Throughput is defined as the amount of data received by
 304 a node per unit time. Fig. 7 shows that for any given value
 305 of P (or D), the throughput of noiseless AODV-P (or AODV-D)
 306 is much lower than the noisy AODV-P (or AODV-D) scheme.
 307 This is trivial and can be explained by considering the packet
 308 losses caused by the noise. However, the important point
 309 here is the difference in how throughput changes with P
 310 (or D) for noisy and noiseless AODV-P (or AODV-D). For
 311 noiseless AODV-P, throughput increases with P , reaches a
 312 maximum value and then starts decreasing but the through-
 313 put of noisy AODV-P increases monotonically with P and is
 314 maximum at $P = 1$ which is pure AODV. Similarly, through-
 315 put increases monotonically with D for noiseless AODV-D
 316 while it decreases monotonically with D for noisy AODV-D.
 317 This shows that the throughput performance of AODV-P
 318

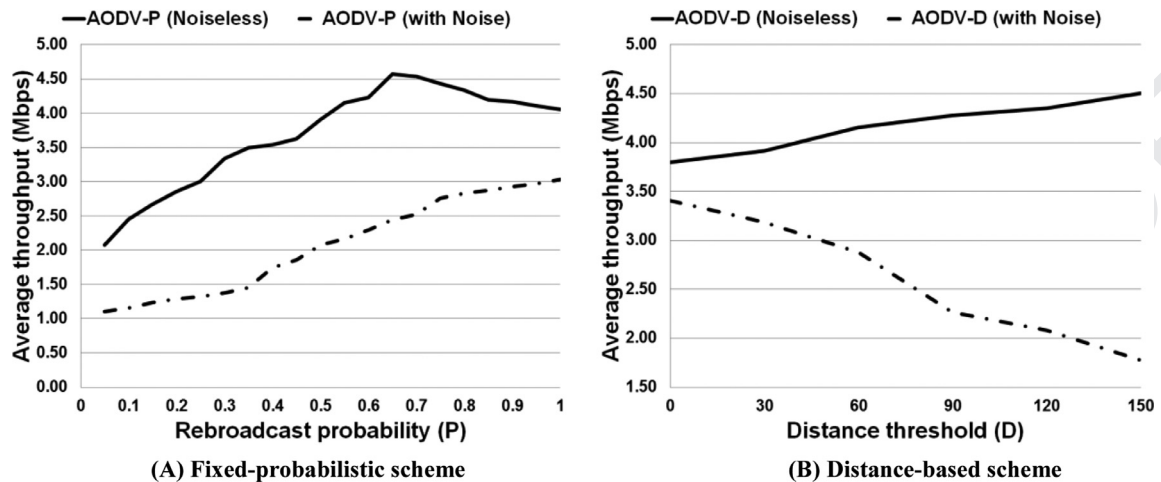


Fig. 7. Average of throughput versus (A) rebroadcast probabilities, (B) distance threshold.

319 and AODV-D is almost reversed when noise is taken into
 320 account.

321 Lower values of P limit the reachability of RREQs. As a
 322 result, the route discovery mechanism may not be success-
 323 ful at first attempt and may have to be initiated repeatedly.
 324 This would increase the time to establish a route from the
 325 source node to the destination node. The FTP application
 326 has to wait longer before it could start sending data. More-
 327 over, node mobility invalidates old routes more frequently
 328 and interrupts the data supply until an alternative route is es-
 329 tablished. The lower the rebroadcast probability will be, the
 330 longer it will take to find the alternative route. This results
 331 in prolonged interruption in data supply that decreases the
 332 throughput further. Increasing the rebroadcast probability
 333 increases the reachability of RREQs and hence the through-
 334 put improves. However, beyond certain value ($P > 0.65$),
 335 the nodes start getting significantly higher number of dupli-
 336 cate RREQs from neighboring nodes that cost network band-
 337 width and the application layer throughput starts reducing
 338 from the peak value of 4.5 Mbps. For AODV-D, by increas-
 339 ing the value of D the number of RREQ packets decreases

340 significantly (see Figs. 4, 5 and 6) that helps to improve the
 341 throughput.

342 In presence of noise, the strategy of limiting RREQ re-
 343 broadcasting harms the performance rather than improving
 344 it. It is because the decision of rebroadcasting RREQ packets
 345 is taken without taking the channel conditions and current
 346 traffic into account. In presence of noise, the throughput in-
 347 creases by increasing the value of P for AODV-P, even beyond
 348 $P = 0.65$, and by decreasing the value of D in AODV-D. In fact,
 349 the side effects of generating redundant RREQ packets by in-
 350 creasing the value of P or decreasing the value of D are di-
 351 minished by noise itself because it acts as a natural limiter
 352 as explained in Section 3.2.1.

3.2.3. Average end-to-end delay

353 Average end-to-end delay shows the time a data packet
 354 takes to arrive from the source node to the destination node
 355 and includes all possible delays caused by route discovery
 356 latency, queuing at the interface queue, retransmission
 357 delays at the MAC layer, propagation delay and transmission
 358 delay at all intermediate nodes. Fig. 8 shows the average
 359

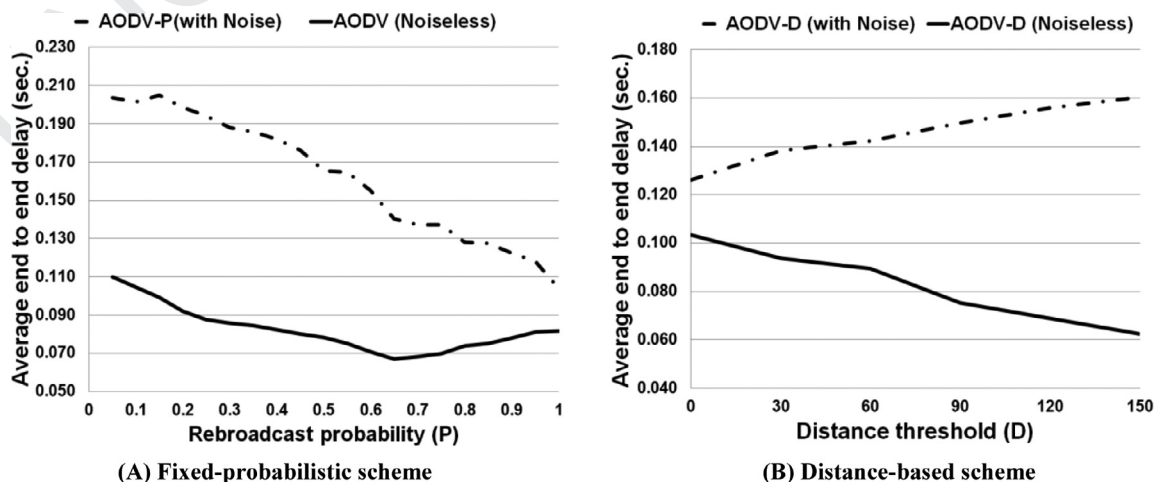


Fig. 8. Average end-to-end delay versus (A) rebroadcast probabilities, (B) distance threshold.

360 end-to-end delay for data packets for all nodes. It can be seen
361 that for any given value of P (or D), the end-to-end delay of
362 noiseless AODV-P (or AODV-D) is much higher than the noisy
363 AODV-P (or AODV-D) schemes. Similar to the throughput
364 case, it is trivial and can be explained by considering the
365 packet losses caused by the noise. However, the effect of
366 the increasing value of P and D on end-to-end delay using
367 AODV-P and AODV-D respectively is almost reversed when
368 noise is taken into account.

369 Lower values of P (or higher values of D) limit the reacha-
370 bility of RREQ packets and the route discovery may fail. Con-
371 sequently, the route discovery may need to be tried several
372 times to get a valid route which increases the end-to-end
373 delay. Higher values of P (or lower values of D) generate ex-
374 cessively large number of RREQ packets which contest with
375 the application layer traffic and consume bandwidth. As a re-
376 sult the end-to-end delay is increased. However, when noise
377 is considered in the simulation, excessive RREQ packets are
378 lost due to interference and do not reach to other parts of
379 the network for rebroadcasting avoiding the broadcast storm
380 problem. That's why the end-to-end delay is not penalized by
381 increasing the value of P (or decreasing the value of D).

382 3.2.4. Average energy consumption

383 Energy consumption accounts for the energy consumed
384 in transmitting, forwarding and receiving of application layer
385 data and routing-related control data. Fig. 9 depicts the aver-
386 age energy consumption of all nodes as a function of rebroad-
387 cast probability P and distance threshold D . For any value of
388 P , the energy consumption of noisy AODV-P is higher than
389 that of noiseless AODV-P. Similarly, for any value of D , the
390 energy consumption of noisy AODV-D is higher than that of
391 noiseless AODV-D. This is because, first, extra energy is con-
392 sumed to compensate losses, second, the routing overhead
393 in presence of noise is much higher than that of the noiseless
394 case (see Fig. 3). This can also be verified by the total number
395 of RREQ packets (broadcasted and rebroadcasted) which are
396 much higher in the noisy case than that of the noiseless case
397 (see Figs. 4–6).

398 In the noiseless case, by increasing the value of P or de-
399 creasing the value of D , the energy consumption increases

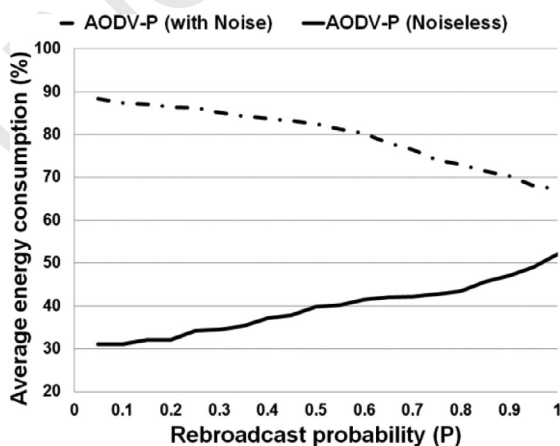
400 but in noisy case it decreases. This is perfectly aligned with
401 the routing overhead that increases in noiseless case but de-
402 creases in the noisy case by increasing the value of P or de-
403 creasing the value of D . In fact, for the noiseless case, by in-
404 creasing the value of P (or decreasing the value of D), even
405 though the reachability of RREQ increases but the RREQ traf-
406 fic shoots up exponentially which is more devastating in
407 terms of energy consumption. When noise is taken into ac-
408 count, increasing the value of P (and decreasing the value of
409 D) does not cause RREQ traffic to shoot up because noise acts
410 as a natural limiter, excessive RREQ traffic is dropped due to
411 inference and does not propagate further which reduces the
412 energy consumption.

413 4. Conclusion and future work

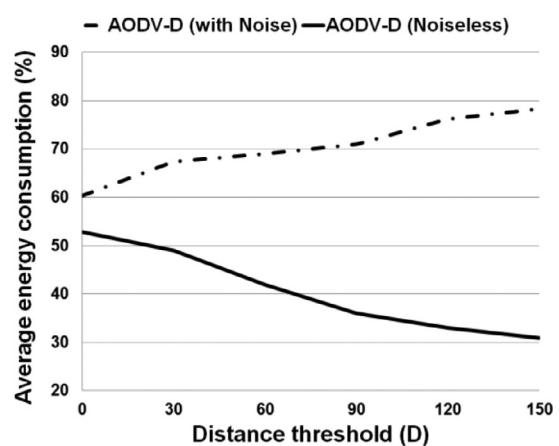
414 Broadcasting is often used in on-demand routing proto-
415 cols to discover new routes in MANETs. A number of proba-
416 bilistic broadcasting schemes have been presented in the lit-
417 erature to limit the number of broadcast messages. However,
418 these approaches were not evaluated under realistic condi-
419 tions and have ignored the effects of thermal noise and co-
420 channel interference which are inherent to real life MANETs.

421 This paper studied the effects of thermal noise and co-
422 channel interference on the performance of two probabilistic
423 schemes from the literature, namely fixed-probabilistic
424 and distance-based broadcast schemes. We adopted the
425 dei80211mr library of ns-2 based on the standard 802.11 g
426 MAC layer protocol. This library uses SINR-based packet
427 level error model by considering thermal noise and co-
428 channel interference. The standard AODV routing protocol
429 was modified to AODV-P and AODV-D by integrating fixed-
430 probabilistic and distance-based broadcasting schemes re-
431 spectively. The performance metrics included routing over-
432 head, throughput, end-to-end delay and energy consump-
433 tion.

434 The ns-2 simulation results revealed that, in contrast to
435 the previous studies, fixed-probabilistic and distance-based
436 broadcasting schemes performed worse than the pure
437 flooding based scheme when thermal noise and co-channel



(A) Fixed-probabilistic scheme



(B) Distance-based scheme

Fig. 9. Average energy consumption versus (A) rebroadcast probabilities, (B) threshold.

interference were taken into account. The simulation results revealed the fundamental problem of fixed- probabilistic and distance-based broadcasting schemes that these schemes try to avoid the broadcast storm problem by limiting the rebroadcasting of RREQs statically and independent of the current traffic intensity. As a result, it may help in some cases while penalize in other cases. In fact co-channel interference acts as an adaptive limiter for traffic and sheds the extra traffic only when the system is overloaded by bursts of RREQs. The performance of AODV deteriorates with fixed-probabilistic and distance-broadcasting schemes when thermal noise and co-channel interference are taken into account. As part of ongoing studies, effects of thermal noise and co-channel interference on dynamic probabilistic schemes will be investigated.

Uncited references

[25]

References

- [1] J. Liu, X. Jiang, Throughput capacity of MANETs with power control and packet redundancy, *IEEE Trans. Wirel. Commun.* 12 (6) (2013) 3035–3047.
- [2] IETF, Mobile ad-hoc networks (MANETs), 2015. [Online]. Available: <http://www.ietf.org/proceedings/53/179.htm>. (accessed: 30.03.15).
- [3] J. Vazifehdan, R.V. Prasad, E. Onur, I. Niemegeers, Energy-aware routing algorithms for wireless ad hoc networks with heterogeneous power supplies, *Comput. Netw.* 55 (2011) 3256–3274.
- [4] N. Battat, H. Seba, H. Kheddouci, Monitoring in mobile ad hoc networks: a survey, *Comput. Netw.* 69 (2014) 82–100.
- [5] C. Ni, H. Liu, A.G. Bourgeois, Y. Pan, An enhanced approach to determine connected dominating sets for routing in mobile ad hoc networks, *Int. J. Mob. Commun.* 3 (3) (2005) 287–302.
- [6] N. Sarkar, W. Lol, A study of manet routing protocols: joint node density, packet length and mobility, *Proceedings of the IEEE Symposium on Computers and Communications (ISCC)* (2010) 515–520.
- [7] T. Clausen, P. Jacquet, Optimized link state routing protocol (OLSR), RFC 3626, IETF Network Working Group (2003) [Online]. Available: <http://www.ietf.org/rfc/rfc3626.txt> (accessed: 25.02.14).
- [8] C.E. Perkins, P. Bhagwat, Highly dynamic (DSDV) for mobile computers routing, in: *Proceedings of the SIGCOMM '94 Conference on Communications Architectures, Protocols and Applications*, 1994, pp. 234–244.
- [9] C. Perkins, E.M. Belding-royer, S. Das, Ad hoc on-demand distance vector (AODV) routing, IETF (2003) [Online]. Available: <https://tools.ietf.org/html/rfc3561> (accessed: 01.05.15).
- [10] C.K. Toh, Associativity-based routing for ad hoc mobile networks, *Wirel. Pers. Commun.* 4 (2) (1997) 1–36.
- [11] Z.J. Haas, M.R. Pearlman, The performance of query control schemes for the zone routing protocol, *Proceedings of the ACM SIGCOMM'98* (1998) 167–177.
- [12] P. Sinha, R. Sivakumar, V. Bahrghavan, CEDAR: a core extraction distributed ad hoc algorithm, *IEEE J. Sel. Areas Commun.* 17 (8) (1999) 1454–1466.
- [13] S.J. Lee, E.M. Belding-Royer, C.E. Perkins, Ad hoc on-demand distance-vector routing scalability, *ACM SIGMOBILE Mob. Comput. Commun. Rev.* 6 (3) (Jun 2002) 94.
- [14] S. Ni, Y. Tseng, Y. Chen, The broadcast storm problem in a mobile ad hoc network, *Wirel. Netw.* (8) (2002) 153–167.
- [15] A. Hanashi, A. Siddique, I. Awan, M. Woodward, Performance evaluation of dynamic probabilistic broadcasting for flooding in mobile ad hoc networks, *Simul. Model. Pract. Theory* 17 (2) (2009) 364–375.
- [16] J. Abdulai, M. Ould-Khaoua, L.M. Mackenzie, Improving probabilistic route discovery in mobile ad hoc networks, in: *Proceedings of the 32nd IEEE Conference on Local Computer Networks (LCN 2007)*, 2007, pp. 739–746.
- [17] A. Qayyum, L. Viennot, A. Laouiti, Multipoint relaying for flooding broadcast messages in mobile wireless networks, in: *Proceedings of the 35th Annual Hawaii International Conference on System Sciences*, 2002, pp. 3866–3875.
- [18] H. Lim, C. Kim, Multicast tree construction and flooding in wireless ad hoc networks, in: *Proceedings of the 3rd ACM International Workshop*

- on Modeling, Analysis and Simulation of Wireless and Mobile System MSWIM '00, 2000.
- [19] M.B. Yassein, M.O. Khaoua, Applications of probabilistic flooding in MANETs, *Int. J. Ubiquitous Comput. Commun.* 1 (1) (2007) 1–5.
- [20] N. Meghanathan, Performance studies of MANET routing protocols in the presence of different broadcast route discovery strategies, *Ubiquitous Comput. Commun. J.* 2 (4) (2007) 86–97.
- [21] A. Mohammed, M. Ould-Khaoua, L.M. Mackenzie, C. Perkins, J.D. Abdulai, Probabilistic counter-based route discovery for mobile ad hoc networks, in: *Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing Connecting the World Wirelessly - IWCMC'09*, 2009, pp. 1335–1339.
- [22] Q. Zhang, D.P. Agrawal, Dynamic probabilistic broadcasting in MANETs, *J. Parallel Distrib. Comput.* 65 (2) (2005) 220–233.
- [23] P. Ruiz, P. Bouvry, Enhanced distance based broadcasting protocol with reduced energy consumption, in: *Proceedings of the 2010 International Conference on High Performance Computing and Simulation, HPCS 2010*, 2010, pp. 249–258.
- [24] H. Al-Bahadili, A. Sabri, A novel dynamic noise-dependent probabilistic algorithm for route discovery in MANETs, *Int. J. Bus. Data Commun. Netw.* 7 (1) (2011) 52–67.
- [25] V. Mathivanan, E. Ramaraj, An analysis of fixed probabilistic route discovery mechanism using on-demand routing protocols, *Int. J. Innov. Technol. Creation Eng.* 1 (12) (2011) 20–27.
- [26] J. Cartigny, D. Simplot, Border node retransmission based probabilistic broadcast protocols in ad-hoc, in: *Proceedings of The 36th Annual Hawaii International Conference on System Sciences (HICSS'03)*, 2002, pp. 6–9.
- [27] Q. Zhang, D.P. Agrawal, Analysis of leveled probabilistic routing in mobile, in: *Proceedings of the IEEE International Conference on Communications, 2004*, pp. 3896–3900.
- [28] S. Kucera, S. Aissa, S. Member, S. Yoshida, Adaptive channel allocation for enabling target SINR achievability in power-controlled wireless networks, *IEEE Trans. Wirel. Commun.* 9 (2) (2010) 833–843.
- [29] F. Abrate, A. Vesco, R. Scopigno, Improvement of WiFi physical model and effects on network simulations, in: *Proceedings of the 2010 International Conference on Wireless Communications & Signal Processing (WCSP)*, 2010, pp. 1–6.
- [30] M. Takai, J. Martin, R. Bagrodia, Effects of wireless physical layer modeling in mobile ad hoc networks, in: *Proceedings of the 2nd ACM International Symposium on Mobile Ad hoc Networking & Computing*, 2001, pp. 87–94.
- [31] F. Alnajjar, Y. Chen, SNR/RP aware routing algorithm: cross-layer design for MANETs, *Int. J. Wirel. Mob. Netw.* 1 (2) (2009) 127–136.
- [32] S. Linfoot, H.Y. Adarbah, B. Arafeh, A. Duffy, Impact of physical and virtual carrier sensing on the route discovery mechanism in noisy MANETs, *IEEE Trans. Consum. Electron.* 59 (3) (2013) 515–520.
- [33] The VINT Project, The new emulator NS-2, 2014. [Online]. Available: <http://www.isi.edu/nsnam/ns/>. [Accessed: 20-Jan-2014].
- [34] H. Lee, Y. Kim, J. Song, AOZDV: An Enhanced AODV Protocol based on Zone Routing in MANET, in: *Proceeding of the International Conference on Wireless Communications, Networking and Mobile Computing, WiCOM 2007*, Sep. 2007, pp. 1685–1688.
- [35] Y. Tseng, S. Ni, E. Shih, Adaptive approaches to relieving broadcast storms in a wireless multihop mobile, *IEEE Trans. Comput.* 52 (5) (2003) 545–557.
- [36] DEI, “NS2 Library: dei80211mr,” 2014. [Online]. Available: <http://www.isi.edu/nsnam/ns/doc/node193.html>. (accessed: 17.02.14).
- [37] X.S. Rajendra, V. Boppana, On the impact of noise on mobile ad hoc networks, in: *Proceedings of the 2007 International Conference on Wireless Communications and Mobile Computing (IWCMC'07)*, 2007, pp. 208–213.
- [38] G. Lin, G. Noubir, R. Rajamaran, Mobility models for ad hoc network simulation, in: *Proceedings of the 23rd Conference of the IEEE Communications Society (INFOCOM 2003)*, 2004, pp. 454–463.



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