Impact of Mobility on the BER Performance of Multi-Hop Ad Hoc Wireless Networks

G. Ferrari[1,2], S. Panichpapiboon[2], N. Wisitpongphan[2], R. Chokshi[2,3], and O. K. Tonguz[2]

[1]Dipartimento di Ingegneria dell'Informazione, Università di Parma, I-43100, Parma, Italy

[2] ECE Department, Carnegie Mellon University, Pittsburgh, PA 15213-3890, USA

[3] Honeywell Labs, Minneapolis, MN 55403, USA

E-mail: `gianluigi.ferrari@unipr.it, tonguz@ece.cmu.edu`

URL: `http://www.ece.cmu.edu/~tonguz`

Abstract— **In this paper, we propose a simple *semi-analytical* approach for the evaluation of the impact of mobility on the bit error rate (BER) performance of multi-hop ad hoc wireless networks. Analytical expressions, relating the BER at the end of a multi-hop route with the mobility characteristics of the nodes and the routing strategy, are derived. Two node mobility models are considered: *direction-persistent* (DP) and *direction-non-persistent* (DNP). In particular, two network switching scenarios are analyzed: (i) *opportunistic non-reservation-based switching* (ONRBS), where a message flows from source to destination by opportunistically choosing the available shortest consecutive links; and (ii) *reservation-based switching* (RBS), where, after the creation of a multi-hop route from source to destination, the message is "forced" to flow over the reserved links, regardless of their actual lengths. The network performance is evaluated in *ideal* (without inter-node interference, INI) and *realistic* (with INI) cases. The improved robustness against mobility offered by ONRBS, with respect to RBS, is analyzed and quantified.**

I. Introduction

Multi-hop ad hoc wireless networks are attracting the attention of many researchers, for their potential to provide ubiquitous connectivity. In particular, in future ad hoc wireless networks, nodes are likely to be *mobile* (e.g., car-based ad hoc wireless networks) [1]. Maintaining multi-hop routes is a challenging task, especially in the case of mobile nodes: the topology is time-varying and, once a route has been established, local *route maintenance* is necessary in order for a route to continue to function when a link is broken.

Recently, a novel communication-theoretic framework for ad hoc wireless networks has been proposed [2], [3]. In particular, the impact of the physical layer characteristics on the network performance, jointly with the used medium access control (MAC) protocol and the specific routing strategy, has been evaluated.

While in [2] a network communication scenario with *static* nodes placed at the vertices of a uniform square grid is considered, in this paper we extend the proposed framework in order to incorporate the effects of node mobility on the performance of ad hoc wireless networks. Rather than relying heavily on computer simulations, we propose a novel *semi-analytical* approach, where the impact of mobility is evaluated from a communication-theoretic perspective. We consider both an *ideal* network communication scenario, without inter-node interference (INI), and a *realistic* network communication scenario, in which communications are affected by INI. In the latter case, we make use of a MAC protocol originally proposed in [2]. Two possible switching strategies, after initial route discovery, are considered: (i) opportunistic non-reservation-based switching (ONRBS), where successive hops from source to destination are dynamically chosen based on their lengths (for example, nodes could be equipped with some location-tracking devices able to evaluate the distance between them); and (ii) reservation-based switching (RBS), where successive hops of the discovered multi-hop route are activated consecutively regardless of their actual lengths. In both cases, the impact of two different mobility models, defined as direction-persistent (DP) and direction-non-persistent (DNP), is evaluated. We point out, however, that the proposed framework can be used for any mobility pattern, provided that a statistical description is available. Numerical results, in terms of average bit error rate (BER), are presented to assess the performance of the considered ad hoc wireless network communication schemes. As expected, ONRBS mitigates the performance degradation, caused by node mobility, more efficiently than RBS. Our results also show that mobility patterns characterized by frequent changes of direction lead to improved performance, and this improvement is more pronounced with RBS, rather than with ONRBS.

II. Preliminaries

The considered ad hoc wireless network communication scenario can be characterized as follows.

- Peer-to-peer multi-hop communications are considered.
- We assume that the routes have already been reserved and we focus on the analysis of the transmission phase following the route creation phase.[1]
- The traffic generation process at each node is described by a Poisson distribution with parameter λ (dimension: [msg/s]).
- No intermediate retransmission mechanism is used.
- We assume that there are N mobile nodes in the network and that they are *confined* to a fixed area A (e.g., an ad hoc wireless network of laptops in a university campus).
- Each node transmits information in terms of messages. In particular, the messages have fixed length M (dimension: [b/msg]) and the transmission data-rate at each node, denoted as R_b (dimension: [b/s]), is fixed as well. Neglecting the propagation time, the duration of a message

[1]The route creation phase, albeit crucial, is beyond the scope of this paper.

transmission between two communicating nodes is $D_P \triangleq M/R_b$.

In order to derive an analytical model which captures the impact of node mobility from a communication-theoretic perspective, we first recall some basic results from the framework proposed in [2], [3]. It is assumed that N nodes are uniformly placed at the vertices of a square grid in a circular area A: each node has therefore four nearest neighbors. Any multi-hop route in the network is given by a sequence of links between nearest neighbors. In [2], it is shown that the distance between two neighboring nodes is $1/\sqrt{\rho_S}$, where $\rho_S \triangleq N/A$ is the node spatial density. In this case, the average BER at the end of a multi-hop route can be written as

$$\overline{\text{BER}} \simeq 1 - (1 - \text{BER}_L)^{\sqrt{N/\pi}} \tag{1}$$

where BER_L is the link BER. In particular, the link BER depends, among other parameters, on the signal-to-noise ratio (SNR) at the ending node of the link, denoted as SNR_L. Expression (1), suitably modified to take into account the effects of mobility, will constitute the starting point of the analysis presented in this paper.

We assume that the transmitted signal is simply affected by free-space loss. Hence, according to Friis free space formula [4], the received signal power at distance d from the transmitter, indicated by $P_r^{(d)}$, can be expressed as follows:

$$P_r^{(d)} = \frac{\alpha P_t}{d^2} = \frac{G_t G_r c^2 P_t}{(4\pi)^2 f_l f_c^2 d^2} \tag{2}$$

where: P_t is the transmitted power from each node; G_t and G_r are the transmitter and receiver antenna gains; f_c is the carrier frequency; c is the speed of light; and $f_l \geq 1$ is a loss factor. In the following, we consider $G_t = G_r = 1$ (omnidirectional antennas) and $f_l = 1$ (no system losses). In the remainder of this paper, we will limit ourselves to schemes with uncoded binary phase shift keying (BPSK), but the proposed approach can be straightforwardly extended to any modulation format.

A general expression for the link SNR is

$$\text{SNR}_L = \frac{P_r^{(r_L)}}{P_{\text{thermal}} + P_{\text{INT}}} \approx \frac{\alpha P_t / r_L^2}{F k T_0 R_b + P_{\text{INT}}} \tag{3}$$

where: P_{INT} is the INI power and depends on the MAC protocol and the spatial distribution of the nodes; F is the noise figure [4], $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann's constant and T_0 is the room temperature ($T_0 \approx 300$ K)—in the case of uncoded BPSK the 3-dB bandwidth is approximately equal to the data-rate R_b. The performance in the ideal (no INI) case is obtained by setting $P_{\text{INT}} = 0$. Explicit expressions for P_{INT} depend on the MAC protocol [2], and preliminary results with ONRBS can be found in [5].

In [2], a MAC protocol based on route reservation and without collision-based retransmission over intermediate links, is proposed for reservation-based switched multi-hop ad hoc wireless networks. The principle of operation of this MAC protocol can be described as follows. A node, after reserving a multi-hop communication route to its destination, activates the route, i.e., starts transmitting, regardless of the activity of the other nodes (not belonging to the reserved route). For this reason, we will refer[2] to this MAC protocol as *reserve-and-go* (RESGO).

In Section V, the impact of the INI when RESGO MAC protocol is used will be evaluated simply by substituting into the link SNR expression (3) the interference noise power expression found in [2]. This is obviously not rigorous, since, because of mobility, the node topology is likely to be far from uniform, so that the considered expression for the average interference power is not extremely accurate. However, due to the assumption that the nodes can not exit the area A and due to the focus of this paper on the analysis of the impact of node mobility (rather than exact characterization of the INI), we will use the simple closed-form expression of the interference noise power, given in [2], to take into account the INI. A more rigorous analysis, that takes explicitly into account various network topologies is currently under investigation.

III. Switching Models

A. Opportunistic Non-Reservation-Based Switching

A source node, in need of communicating with a destination node, does not reserve in a static way intermediate relay nodes. Instead, consecutive links, from source to destination, are chosen *opportunistically*, based on their lengths. In other words, at the moment of route creation a "tentative" multi-hop route (or, possibly, more than a single multi-hop route) from source to destination is created. Afterwards, we assume that there is *adaptive* maintenance of the route links. More precisely, if two consecutive nodes (constituting a link) of the originally created route move too far from each other, the starting node of this link will choose another node at average distance $1/\sqrt{\rho_S}$. For the sake of simplicity, we assume that a node at distance $1/\sqrt{\rho_S}$ can always be found. Note that it might happen that a neighboring node at distance $1/\sqrt{\rho_S}$ is not immediately present: in this sense, the overall transmission from source to destination might suffer an additional delay. Moreover, opportunistic link creation/activation from source to destination might require a significant exchange of control messages among the intermediate nodes in the multi-hop routes, reducing the overall transfer of "useful" information—this is the price to pay for increased robustness against mobility, as will be shown in Section V. Further research is needed to address these important aspects of ONRBS-based ad hoc wireless networks.

B. Reservation-Based Switching

In this case, during the route discovery process, intermediate relay nodes are reserved in a static way. In other words, once a route is created, the order of the intermediate relay nodes does not change for the entire duration of the transmission,

[2]This MAC protocol was referred to in [2] as Aloha MAC protocol, for its resemblance, in terms of route activation being independent from the activity of other nodes in the network, to the classic Aloha MAC protocol. However, there are significant differences which make RESGO MAC protocol different from the classic Aloha MAC protocol: (i) multi-hop route reservation and (ii) no use of retransmission techniques.

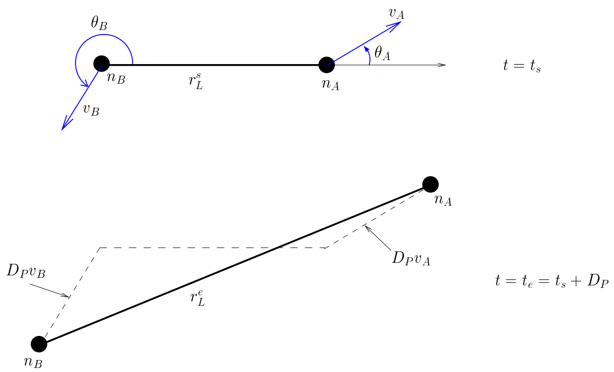

Fig. 1. Link evolution during a message transmission in the case of direction-persistent (DP) mobility model.

regardless of the actual lengths of the links. Obviously, for a sufficiently high node mobility level, even assuming that the *initial* set-up of a multi-hop route is characterized by a sequence of hops with average length $1/\sqrt{\rho_S}$, the lengths of the final links of the route could significantly change, at the moment of their activation, with respect to their initial lengths. Hence, we expect that the robustness of RBS to node mobility is significantly reduced with respect to that of ONRBS. This degradation is limited if the mobility pattern is characterized by frequent changes of direction.

IV. Mobility Models

The *mobility status* of a node can be described in terms of two random processes: *speed* v and *direction angle* θ (with respect to a horizontal axis). Two possible mobility models are considered in the following, but we underline that the proposed approach is applicable in other cases, provided that a statistical description of nodes' mobility is available.

A. Direction-Persistent Mobility Model

In this case, during a message transmission on a single link, the direction and speed of the two nodes at the ends the link are constant. Based on this assumption, we now investigate how this mobility model can be combined with the two considered routing strategies.

1) Opportunistic Non-Reservation-Based Switching: Consecutive links are assumed to be "independent" from each other. More precisely, the mobility status of a node during a message transmission on a link (where such a node is the final node) will be independent from its mobility status during the message transmission on the consecutive link (where such a node is the starting node).

Under the assumption of a DP mobility model, we now analyze the evolution of a link (corresponding to any intermediate link of a multi-hop route) during a message transmission. We denote the two nodes of the link as n_A and n_B. We assume that these nodes have constant speeds and direction angles, indicated as (v_A, θ_A) and (v_B, θ_B), during the transmission of a message. The link status at the activation (t_s) and at the end ($t_e = t_s + D_P$) of a message transmission are shown in Fig. 1. Simple geometric considerations allow one to express the final link length r_L^e as

$$\begin{aligned} r_L^e \quad = \quad & \left\{ r_L^2 + D_P^2 (v_A^2 + v_B^2) - 2 v_A v_B D_P^2 \cos(\theta_A - \theta_B) \right. \\ & \left. + 2 r_L D_P (v_A \cos\theta_A - v_B \cos\theta_B) \right\}^{0.5}. \qquad (4) \end{aligned}$$

In order to make a simple performance analysis, we consider the arithmetic mean between $r_L^s = r_L$ and r_L^e as a meaningful average link length, i.e.,

$$\overline{r}_L \quad \triangleq \quad \frac{r_L^s + r_L^e}{2}. \qquad (5)$$

At this point, we assume that the average link SNR during the transmission of a message can be obtained from (3), provided that r_L is replaced by $\overline{r}_L$.

In general, a Monte Carlo simulation-based approach for the evaluation of the BER at the end of an average communication route can be considered. For the sake of simplicity, the mobility patterns of different nodes are assumed to be independent. We define as $\zeta_i \triangleq (v_i, \theta_i, v_{i+1}, \theta_{i+1})$ the ensemble of speed and direction angle realizations of the two nodes constituting the i-th link, $i \in \{1, \ldots, \overline{n}_h\}$, during transmission of the message across the i-th link.[3] Clearly, $\overline{r}_L = \overline{r}_L(\zeta_i)$. We denote the i-th link BER, corresponding to the realization ζ_i, as $\mathrm{BER}_L(\zeta_i)$. Hence, the final BER at the end of an average communication route corresponding to an overall realization ensemble,[4] denoted as $\zeta_{\mathrm{ONRBS}} \triangleq (\zeta_1, \ldots, \zeta_{\overline{n}_h})$, can be written as

$$\mathrm{BER}(\zeta_{\mathrm{ONRBS}}) \approx 1 - \prod_{i=1}^{\overline{n}_h} \left[1 - \mathrm{BER}_L(\zeta_i)\right]. \qquad (6)$$

Considering a sufficiently large number η of *realization ensembles*, i.e., $\zeta_{\mathrm{ONRBS}}^{(j)} = \left(\zeta_1^{(j)}, \ldots, \quad \ldots, \zeta_{\overline{n}_h}^{(j)}\right)$, $j \in \{1, \ldots, \eta\}$, an estimate of the average BER can be written as

$$\overline{\mathrm{BER}} = \frac{\sum_{j=1}^{\eta} \mathrm{BER}(\zeta_{\mathrm{ONRBS}}^{(j)})}{\eta}. \qquad (7)$$

2) Reservation-Based Switching: Once a multi-hop route has been created, a message flows through the originally reserved links of the route, regardless of their evolution (due to possible nodes' movement). This is based on the assumption that the mobility status of each node remains constant for the entire message transmission along the activated route.

The approach considered in Subsection IV-A.1 for the evaluation of the BER in a network communication scenario with ONRBS, can be extended to the case with RBS. The only difference consists of the fact that speed and direction angle

[3]Note that $(v_B^{(i)}, \theta_B^{(i)})$ and $(v_A^{(i+1)}, \theta_A^{(i+1)})$ are the two consecutive mobility status of the same node. In the case of ONRBS, we assume that they are independent. This implies that the same node is associated with two different mobility status on a link where it is the final node and in the following link where it is the starting node.

[4]Note that, due to ONRBS, it might happen that the number of hops between a source and destination pair is actually larger than $\overline{n}_h$. However, in order to make a simple and meaningful comparison with the case of RBS, we assume that the total number of hops from source to destination is still, on average, $\overline{n}_h$.

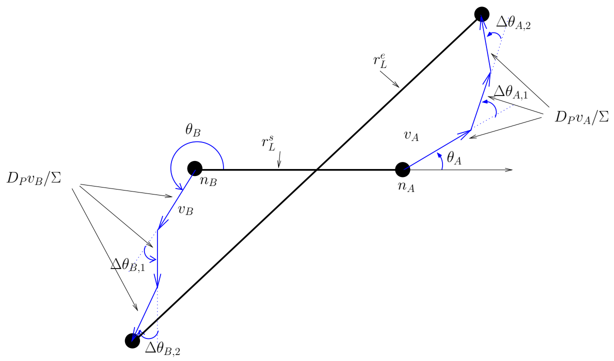

Fig. 2. Link evolution under the assumption of DNP mobility model, with $\Sigma = 3$ different movement directions within the duration of a message transmission.

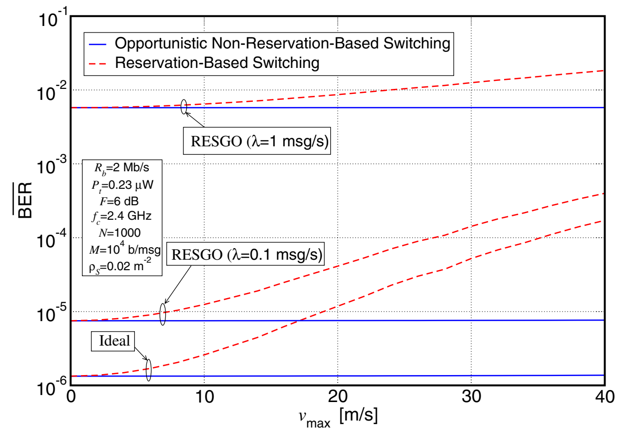

Fig. 3. BER versus maximum node speed, in the case of DP mobility model. Ideal (no INI) and realistic (presence of INI with RESGO MAC protocol and various traffic loads) cases are considered.

of a node do not change for the entire duration of the message transmission from source to destination (details not reported here for lack of space [3]).

B. Direction-Non-Persistent Mobility Model

Unlike in a network communication scenario characterized by a DP mobility model, in a scenario characterized by a DNP mobility model a node can change the *direction* of movement during the transmission of a message. In particular, we "break" the message duration into a finite number Σ of subintervals (or slots) of equal duration. The distance covered by a node in a slot is equal to $D_P v/\Sigma$. While the speed of a node remains constant for the entire message duration, the direction angle can change from slot to slot. In particular, the angular change $\Delta\theta$ at the end of a slot can be considered as a function of the speed: intuitively, the faster a node is moving, the smaller the change of direction can be—a more specific model will be introduced in Section V. In Fig. 2, a pictorial example of the evolution of the link between two neighboring nodes (in the case with $\Sigma = 3$ slots per message duration) is shown. The derivation in Subsection IV-A can be extended to this case, by suitably computing the average link lengths slot by slot.

V. Numerical Results

In the following, the results are separated according to the considered mobility model, either DP or DNP. In both cases, in order to use the proposed semi-analytical Monte Carlo technique, a sufficiently large number η of independent realizations is considered. The major network parameters are indicated in the figures. In particular, the very low transmitted power ($P_t = 0.23\,\mu$W) can be considered as typical of a wireless micro-sensor network—the corresponding receiver sensitivity is around -93 dBm (the distance between neighboring nodes is approximately 7 m and there is only free space propagation loss).

A. Direction-Persistent Mobility Model

We assume that for each node the speed v is uniformly distributed in $[0, v_{\max}]$ and the angular direction θ is uniformly distributed in $[0, 2\pi)$. In this case, the DP mobility model thus corresponds to the *random waypoint mobility model* [6].

In order to understand the impact of the speed on the BER performance, in Fig. 3 the BER is evaluated as a function of the maximum speed $v_{\max}$, in an ideal case and in a realistic case with RESGO MAC protocol. Two possible values of the traffic load ($\lambda = 0.1$ msg/s and $\lambda = 1$ msg/s) are considered in the latter case. The node spatial density is fixed to $\rho_S = 0.02$ m^{-2} and the considered number of nodes is $N = 10^3$. As one can see, the impact of the routing strategy is significant, especially in the ideal case. For increasing values of the maximum speed $v_{\max}$, while the BER in the ONRBS case does not change (the maximum speed should be increased much more to notice a performance degradation), the BER in the RBS case rapidly degrades, increasing almost proportionally to $v_{\max}$. In fact, an RBS scheme is characterized by the fact that nodes do not change direction of movement during the entire duration of the message transmission, which is equal (neglecting the propagation time) to $D_P \times n_{\mathrm{h}}$, where $n_{\mathrm{h}} \propto \sqrt{N}$ is the number of hops in a route. Therefore, if the maximum speed is large, it follows that the nodes of the last links of a route can move very far from each other, with respect to their original positions, so that the BER at the end of a route significantly degrades. On the other hand, in the case of ONRBS, each link is opportunistically activated and the corresponding nodes do not move significantly, for all considered values of the maximum speed, during the duration of message transmission D_P. In a realistic network communication scenario, the higher the traffic load, the lower the impact of mobility. In other words, higher the INI, lower is the impact of the routing strategy on the performance. In particular, the results in Fig. 3 have practical implications: given a maximum acceptable BER at the end of an average multi-hop route, and given the routing strategy and the traffic load, it is possible to determine the maximum speed which can be supported by the ad hoc wireless network.

In Fig. 4, the dependence of the BER on the message length is shown in the case of very low node mobility level ($v_{\max} = 2$ m/s). As one can observe, for increasing message length (i.e., transmission duration), the BER reaches 1, i.e., the performance becomes unacceptable. While in the ideal case there is a significant difference between the performance with ONRBS and RBS (e.g., at a tolerable BER$^{\max}$=10^{-3}, the maximum message length supported with ONRBS is

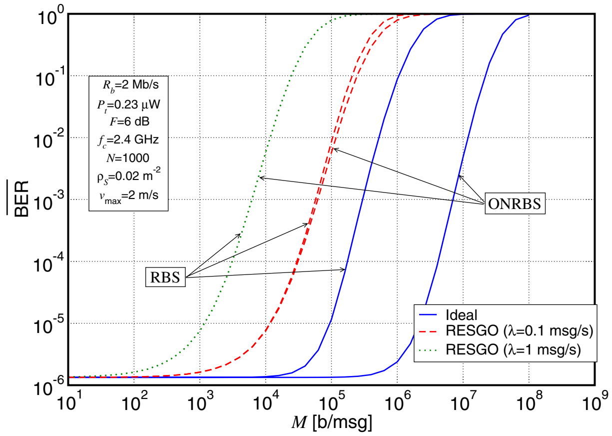

Fig. 4. BER performance versus message length M, in the case of DP mobility model. The maximum speed is $v_{\max} = 2$ m/s. Ideal (no INI) and realistic (with INI, RESGO MAC protocol and various traffic loads) cases are considered.

$M \approx 7 \times 10^7$ b/msg, whereas that supported with RBS is $M \approx 3 \times 10^5$ b/msg), in a realistic case, the difference between ONRBS and RBS is negligible—this is also predicted by the results, for low values of $v_{\max}$, shown in Fig. 3. It is possible to show that an increase of the maximum speed has a dual effect: (i) for a given maximum acceptable BER, the maximum acceptable message length becomes significantly lower; and (ii) the performance difference between the two considered switching techniques is still substantial in a realistic network communication scenario with moderate traffic load.

B. Direction-Non-Persistent Mobility Model

As mentioned in Subsection IV-B, intuitively it is obvious that the faster a node is moving, the less pronounced the direction changes during a single message transmission can be. In order to formalize this intuition, we assume that the direction change $\Delta\theta$ between two consecutive slots can be written as follows:

$$\Delta\theta = \pm\Delta\theta_{\max}\left(1 - e^{-\frac{1}{v}}\right) \tag{8}$$

where: v is the speed of the node (constant for the entire message transmission); $\Delta\theta_{\max}$ corresponds to the maximum considered change of angular direction of movement; and the sign in front of the angular deviation (+ or -) is chosen randomly and independently in consecutive slots. In order to evaluate the impact of the proposed DNP mobility model with respect to that of the DP mobility model, the following analysis is limited to an ideal (no INI) case. The extension to a realistic (INI) case is straightforward (omitted here due to lack of space).

In Fig. 5, the BER performance with RBS is shown as a function of the node spatial density. The maximum speed is set to $v_{\max} = 2$ m/s. Three possible values for the parameter Σ (1, 2, and 5) and two possible values for the maximum angular deviation $\Delta\theta_{\max}$ ($\pi/4$ and π) are considered. Observe that an increase of Σ and/or $\Delta\theta_{\max}$ has a beneficial effect on the BER performance. In fact, in the RBS case, the final nodes of the route (i.e., those close to the destination), rather than moving far apart, are more likely forced to move around their original

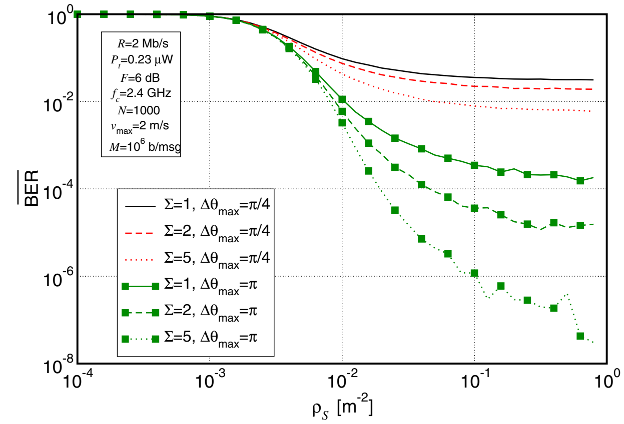

Fig. 5. BER performance, in an ideal case, as a function of node spatial density ρ_S, in the case of DNP mobility model with RBS. Various values of the parameter Σ and the maximum angle deviation $\Delta\theta_{\max}$ are considered.

positions because of the frequent changes of direction. The improvement caused by frequent changes of direction is less pronounced if ONRBS is used.

VI. Conclusions

Many factors affect the performance of ad hoc wireless networks, among which node mobility plays a significant role. While routing is usually studied by assuming perfect connectivity, in this paper we have proposed a simple semi-analytical approach, based on communication-theoretical principles, to investigate the relation between node mobility, routing strategy, and physical layer characteristics. The proposed framework can be used together with *any* mobility model, provided that a suitable statistical description is available. Our results show that the use of ONRBS allows to support, at the cost of heavier control traffic, a higher mobility level than the use of RBS. We also showed that the larger the traffic load (and, consequently, the INI), the lower is the impact of the routing strategy (i.e., RBS versus ONRBS) on the network performance. Two mobility models, namely DP and DNP, have been considered. Our results show that, in RBS-based ad hoc wireless networks, a DNP mobility model leads to a better performance, since frequent changes of directions average out, forcing the nodes to move around their original positions in a route, rather than moving far away and, therefore, disrupting connectivity.

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