Assessing the impact of physical layer techniques on ad hoc network performance ⋆

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Abstract

This article provides an overview on the topic of ad hoc network performance analysis, mainly from a physical layer standpoint. The emphasis of the paper is on how the individual link and network performance can be evaluated in an analytically tractable manner, such that design insights can be obtained and optimization over key parameters is possible. Our model is that of a large random network, where the wireless channel comprises path-loss and fading. Various physical layer factors are taken into account: the multiple-access (MA) scheme, such as direct-sequence (DS) CDMA and frequency-hopping (FH) CDMA; error correction coding such as Reed-Solomon (RS) or convolutional coding; coherent or non-coherent detection; the use of multiple-input multiple-output (MIMO) techniques to enhance error protection or to increase the transmission rate. The performance of the network is evaluated and optimized in terms of useful metrics such as the *network throughput*, the *information efficiency* and the *transmission capacity*.

Key words: Ad hoc networks, Poisson random field, DS-CDMA, FH-CDMA, multiple-input multiple-output (MIMO), network throughput, transmission range

1 Introduction

The design and analysis of ad hoc networks presents many challenges, mainly due to the absence of a specific infrastructure. Indicatively, the capacity region

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of an ad hoc network, in the information theoretic sense, remains an open problem within the research community. However, meaningful and intuitive metrics such as the *transport capacity*, i.e. the total number of bit-meters transmitted over a given time within a unit area, introduced in [1], allow us to quantify the network performance. In this seminal paper, the authors studied how the transport capacity scales with the number of nodes, for a very general class of networks.

Although the framework of [1] provides fundamental theoretical bounds, it appears hard to accommodate detailed physical layer and channel models. We are interested in a framework that allows us, in a straightforward way, to evaluate how our physical layer choices are reflected on the overall network performance. The approach discussed in this paper - taken in a number of papers that will be discussed in the sequel - is that of assuming that the network consists of a Poisson random field of transmitters (TXs), each with a respective receiver (RX) at a fixed transmission distance (see Fig.1). This model can be considered as a snapshot of a multi-hop network in time. In the absense of scheduling, all the TXs transmit a packet (in a synchronized manner) independent of their positions, whereas, if some sort of scheduling rule is in effect, a portion of the TXs might remain silent. The topology of the TXs remains constant over one or several packet intervals, until a new realization of the random field, e.g. due to mobility, is generated. The network performance can be evaluated once the average - with respect to the topology - packet throughput of each link is characterized.

We consider metrics such as the *network throughput*, i.e., the product (spatial density of TXs) $\times$ (link spectral efficiency), which addresses the need to pack as many possible transmissions in space, while maintaining a desirable throughput per link; the *information efficiency*, defined as the product (transmission distance) $\times$ (link spectral efficiency), which captures the trade-off present in a multi-hop network, where transmitting farther means a packet needs fewer hops to reach its final destination, however, for a fixed TX power, the RX signal-to-interference (SIR) ratio is lower; and the *transmission capacity*, defined as the maximum allowable density of TXs, such that a performance constraint per link is satisfied, multiplied by the spectral efficiency of each link.

There are two distinct approaches in characterizing the link performance which clearly depend on our assumptions regarding the channel model and the physical layer MA scheme. Under the *outage probability* approach, the TX-RX channel, which generally includes fading and interference from other TXs [1], is constant during the transmission of the packet. The packet is successfully received, if the SIR is larger than a certain threshold; otherwise, an *outage* occurs and the packet is lost. This approach implies that the packet is protected

[1] We consider interference limited networks, i.e. the effect of AWGN is ignored.

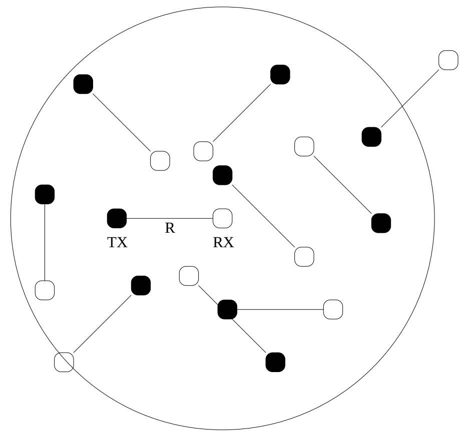

Fig. 1. A realization of Poisson random field of TXs (black nodes) around the typical RX (finite disc shown). According to the properties of the Poisson random field, the TXs are uniformly distributed around the RX.

by a powerful error correcting code, such that the conditional frame-error-probability (FEP) as a function of the SIR, for a given modulation order, resembles a step function around the threshold. If the locations of the interfering TXs and the fading realization are such that the SIR is lower than the threshold, the packet is lost. In information theoretic terms, if all nodes are transmitting symbols from a Gaussian alphabet, the channel mutual information is less than the desired information rate.

Alternatively, the channel can vary during the transmission of a packet. This can be due to actual time variation of fading [2] or due to *effective* variation of the SIR caused by hopping to a new frequency every few symbols in the packet. The advantage of FH across the packet is that interference can be randomized and symbol errors due to collisions can be corrected by interleaving and moderate error correction coding. Since an "averaging" over different channel states takes place within a packet, the allowable information rate of the typical TX-RX link is upper-bounded by the *ergodic* capacity of each link.

What follows is an overview of related work to date, grouped under either of the two previous categories. Our objective is to provide the reader with an outline of the main results and a useful list of references. A special section is devoted to the authors' own work on the evaluation of a FH-MIMO physical layer for ad hoc networks. The paper is concluded by a discussion on topics for future research.

[2] We have reasonably assumed that the topology of the network is constant for at least the packet duration.

2 Constant channel during packet transmission

The properties of the Poisson spatial process were used for the first time in [2], in order to prove that, for a path loss law $r^{-b}, b > 2$, the interference power follows the α-stable distribution with exponent $\alpha = 2/b$. In the special case $b = 4$, the authors obtained closed form expressions for the outage probability, P_o, for a DS-CDMA system with processing gain M. They showed that the optimum transmission distance, in the sense of maximizing the expected forward progress $R \times (1 - P_o)$, is such that the expected number of nodes within the transmission range, R, is proportional to $\sqrt{M}$. The results of this paper were extended in [3] for channels that include fading and shadowing.

A DS-CDMA physical layer with adaptive modulation is investigated in [4,5]. The modulation order is adapted at the TX, depending on the SIR level at the RX. Naturally, lower modulation orders imply a lower SIR threshold for which an outage occurs. Information efficiency is the authors' metric of choice, since it reflects not only the forward progress a packet makes to its final destination over a hop, but also the amount of information transmitted over that hop. The results in [5] demonstrate an intuitive trade-off: the maximum information efficiency can be achieved by transmitting at a high rate over short distances or, at a lower rate, over larger distances. The former strategy, however, is more sensitive to the availability of local relays; in a practical setting, if the transmission distance R is too short, the probability that no RX node exists at that distance is higher.

In [6], the authors consider two MA schemes: DS-CDMA with processing gain M and *interference avoidance* [3] (IA), if the bandwidth is divided into M bands. For a channel with path loss only, they provide upper and lower bounds on the transmission capacity of the network, i.e. the maximum allowable density of TXs, λ_ϵ, such that the outage constraint $P_o \leq \epsilon$ is satisfied. It is shown that, for a given R, $\lambda_\epsilon^{\mathrm{DS}}$ scales with M^α, while $\lambda_\epsilon^{\mathrm{IA}}$ grows linearly with M. The interpretation of this result lies in the fact that interference suppression via spreading/despreading is not as effective as IA; no matter how large M is, it is possible, due to the random nature of the network, for an interfering TX to be very close to the intended RX, thus causing large ammounts of interference (the well known near-far problem). Compared to DS-CDMA, IA provides a gain in transmission capacity of the order $M^{1-\alpha}$, which becomes larger for decreasing α (increasing b). It is also interesting to note that both DS-CDMA and IA do not increase the transmission capacity per unit bandwidth. In fact, in the case of DS-CDMA, $M^{\alpha-1}$ goes to zero for increasing M. However, DS-

[3] Interference avoidance is slow FH, in the sense that hopping takes place at the packet level. We reserve the term FH-CDMA to denote hopping at the symbol level, i.e. hopping at every symbol or once every few symbols.

CDMA enables the use of multi-user detection, e.g. successive interference cancellation, that can potentially increase the capacity, provided that the information regarding the channels of the dominant interferers is accurate [7,8]. Moreover, the transmission range R, for a given density λ and outage constraint ϵ, scales as $M^{\alpha/2}$ for DS-CDMA and $\sqrt{M}$ for IA [6,8]. This indicates the potential for longer transmissions, thus smaller end-to-end packet delays in a multi-hop network (see [9] for a discussion on the benefits of long hops).

In the recently published [10], fading is introduced in the simple channel model of [6] and its impact on the transmission capacity is explored. By deriving bounds on the distribution of the SIR, the authors demonstrate that fading reduces the transmission capacity. However, if a simple threshold-based transmission rule is used, where the TXs are active only when the channels to their respective RXs are acceptably strong, significant capacity gains can be obtained. This result is a manifestation of the *multi-user diversity* effect in the context of a random network.

Using the transmission capacity as a metric, the benefit of different spatial diversity techniques, when the nodes are equipped with multiple antennas, is evaluated in [11]. The mathematical framework of this paper is based on the derivation of the SIR distribution when more than one spatial degrees of freedom are available. Various single-user [4] spatial diversity techniques are considered, such as maximal ratio combining (MRC), eigen-beamforming (EBF), selection combining and orthogonal space-time block coding (OSTBC). If the number of antennas at the TX and the RX are m_t and m_r, respectively, it is shown, e.g. that λ_ϵ scales as m_r^α for MRC, $(m_t m_r)^\alpha$ for EBF and m_r^α for OSTBC. A notable result is that, even though the diversity order of an OSTBC scheme is $m_t m_r$, the gain in terms of transmission capacity is only of the order of m_r^α. This is due to the fact that the interference in the network is amplified by the transmission of independent streams from the TX antennas. These results outline the superiority of beamforming and RX diversity techniques in terms of network capacity.

The work presented in the previous paragraphs considered networks with absolutely no coordination between the nodes. In [12], the effect of scheduling on the transmission capacity of a DS-CDMA ad hoc network is explored. A guard zone rule is enforced in the network, such that any TX within a certain distance of a RX other than its own is not allowed to transmit. As a result, a trade-off between the density of transmissions and the amount of MA interference (MAI) is created. The optimum guard zone is derived and it is shown that the capacity gains are large, such that DS-CDMA can actually outperform IA. The caveat is of course the signaling overhead associated with the scheduling decisions. A short discussion on MAC protocols for DS-CDMA ad

[4] Multi-user MIMO techniques require cooperation between the nodes.

hoc networks is also provided in [8].

3 Channel averaging during packet transmission

FH-CDMA is a widely used technique in wireless systems (for an overview and references, see chapter 13 of [13]). Its resistance to jamming and hostile interception also make it popular for military applications. Coding combined with FH exploits *frequency diversity*, if the fading varies over the hopping distance, and *interference diversity*, provided that the level of interference varies across hops. Several papers in the past have dealt with the performance analysis of FH systems under MAI and partial band interference (PBI) when non-coherent modulation is employed with RS or convolutional codes (see for example, [14, 15]). A common feature of FH systems is that the decoder performance can be dramatically improved if it is aware of the interference levels across the packet. A RS decoder declares an erasure when a symbol has been hit; similarly, a Viterbi decoder weighs the metrics by the respective interference powers. In the context of ad hoc networks, [15] was one of the early papers to discuss the gains in terms of network throughput, compared to a narrowband system.

In [4], the impact of the code rate on the information efficiency of an ad hoc network is studied, when FH with RS coding are employed at the physical layer. The average symbol error probability for FSK modulation, Rayleigh fading and α-stable interference (in the case $\alpha = 1/2$) is analytically evaluated and used to compute the codeword error probability at the RS decoder. As in [5], it is concluded that, in terms of maximizing the information efficiency, it is preferable for a TX to use a high code rate and a small R than a low code rate and a large R.

Recently, [16] extended the work of [4] by considering a more complicated channel and physical layer model. The nodes are equipped with multiple antennas and differential unitary space-time modulation (DUSTM) is employed to achieve spatial diversity in a time-varying fading channel which is not known at the RX. A joint detection and estimation algorithm is developed in order to detect the transmitted symbols and estimate the interference power within the hopping dwell, so that the decoder is capable of erasure insertions. Using information efficiency as their network metric, the authors demonstrate the effect of physical layer factors such as the number of antennas, the shadowing time variation and the Doppler spread on the optimum transmission range.

Motivated by the fact that multiple antennas can be used not only to obtain spatial diversity but also to increase the information rate, [17] considers a variety of MIMO techniques for ad hoc networks; MRC and OSTBC - which were also studied in [11] - as well as *spatial multiplexing* (SM), via *zero forcing* (ZF). The goal of this work is to determine which MIMO strategies are more beneficial in terms of network performance.

Due to the advantages highlighted in the previous section, FH-CDMA is selected as the MA scheme. Instead of differential modulation or non-coherent detection with RS coding, bit-interleaved coded modulation (BICM) [18] with coherent detection is considered. The reasons for this choice are: (a) MRC, OSTBC and SM-ZF require knowledge of the fading matrix at the RX in each hopping dwell, (b) coherent detection provides a gain over non-coherent detection or differential modulation, albeit at the cost of having to estimate the channel in each dwell and (c) the analysis yields compact expressions that indicate clearly how the link and therefore network performance depend on the code parameters and the choice of MIMO scheme.

The TX-RX diagram is shown in Fig.2. The packet information bits are encoded, interleaved and mapped to symbols from a QAM constellation. The symbols are the input to the MIMO block, which, in the case of OSTBC, generates an appropriate space-time matrix, while, for SM, it simply feeds the symbols in parallel to the TX antennas. Depending on the duration of the dwell, after a number of symbol matrices/vectors have been transmitted, a new frequency is selected by the - random - hopping pattern. The fading coefficients of the channel matrix are assumed independent, Rayleigh and constant across the dwell. As shown in Fig.3, a certain portion of the dwell is dedicated to the transmission of training symbols such that the fading matrix and the interference power can be estimated [5] at the RX. The received symbols and the estimated channel state information are the input to the Viterbi decoder which decides what is the most likely codeword/packet to have been transmitted.

[5] We assume synchronization of the links at the dwell level, which is actually a worst-case interference scenario.

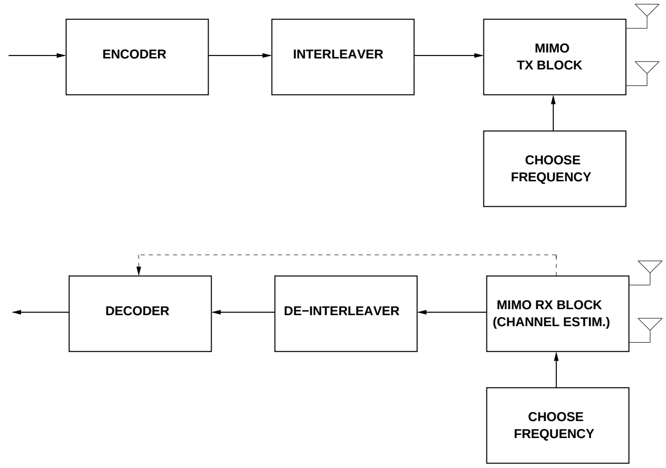

Fig. 2. Block diagram of the TX and the RX.

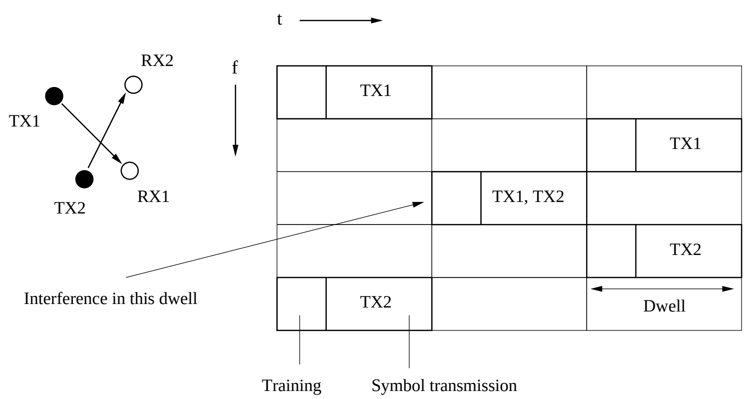

Fig. 3. A FH-CDMA system with two links.

4.1 Mathematical formulation

If x_k is the k^{th} transmitted packet symbol, it can be shown that the equivalent channel model at the input of the RX decoder is

$$y_k = \sqrt{a_k} x_k + w_k. \tag{1}$$

The random variable (r.v.) α_k is chi-square with $2N$ degrees of freedom, where N is the *spatial diversity order* of the MIMO scheme. If the RX has m_r antennas, then, for MRC, $N = m_r$; for the Alamouti OSTBC, $N = 2m_r$ [19]; for SM with ZF, $N = m_r - m + 1$, where $m = 1, \ldots, m_t$ is the number of active streams [20]. In SM mode, a trade-off exists between spatial diversity and rate, as $m - 1$ spatial degrees of freedom are used up for the suppression of the interference caused by the other streams. The r.v. w_k represents the total interference from all active TXs in the dwell. It is Gaussian, given its power, z_k, which, as noted in section 2, follows the α-stable distribution with stability exponent $\alpha = 2/b$.

The RX estimates $\{a_k\}$ and $\{z_k\}$ and decides that $\hat{\boldsymbol{x}}$ was the transmitted codeword according to the maximum likelihood criterion (for BPSK modulation)

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} \left\{ \sum_k \frac{|y_k - \sqrt{a_k} x_k|^2}{z_k} \right\}. \tag{2}$$

The performance of the decoder is characterized by the FEP, P_F, which is approximated by [21]

$$P_F \simeq L_i \sum_{l=L,L+1,\ldots} d_l P_l, \tag{3}$$

where L_i is the number of information bits; P_l is the probabity of an error event of length l; d_l is the number of error events of length l and L is the smallest possible length of an error event or the *diversity order* of the code.

4.2 Link and network performance results

For sufficiently small values of P_l (< 0.01), it can be shown that [17, 22]

$$P_l \simeq \frac{2^{4\alpha l-1}}{\pi} B(\alpha l + 1/2, \alpha l + 1/2) \left(\lambda_{\text{eff}} \alpha B(N-\alpha, \alpha) m^\alpha d_s^{-2\alpha}\right)^l, \tag{4}$$

where d_s is the minimum distance in the QAM constellation and the effective density,

$$\lambda_{\text{eff}} = \frac{\lambda \pi R^2}{M},$$

is defined as the ratio of the expected numbed of TXs in the transmission range over the number of frequencies M. The effective density multiplied by the factor m^α reflects the amount of MAI in the network per RX antenna and unit of bandwidth. Equation (4) reveals that, the higher the diversity order of the convolutional code, the steeper the decrease of P_l for decreasing λ_{eff}. Moreover, N introduces a gain via the factor $B(N-\alpha, \alpha)$. It is easy to prove that, for increasing N,

$$B(N-\alpha, \alpha) \sim \Gamma(\alpha) N^{-\alpha}. \tag{5}$$

Therefore, the factor $(m/N)^\alpha$, namely, the ratio of the number of independently transmitted streams over the spatial diversity order N, raised to the stability exponent, roughly determines the impact of a MIMO scheme on the performance. This is in agreement with the results in [11].

The spectral efficiency (SE) of the typical TX-RX link is determined by the bits/s/Hz that can be transmitted under a given constraint on P_F. For sufficienty small values of P_F, the first term in (3), corresponding to the shortest error event, provides a good approximation to P_F. Imposing the constraint

$P_F = \epsilon$ and assuming continuous rate adaptation, the SE of the link is

$$\nu = \log_2 \left(1 + K \frac{\alpha^{-1/\alpha} B(N-\alpha,\alpha)^{-1/\alpha}}{m} \lambda_{\text{eff}}^{-1/\alpha} \right), \tag{6}$$

where

$$K \triangleq \frac{3}{8} \left(\frac{2\pi\epsilon}{L_i d_L B(\alpha L + 1/2, \alpha L + 1/2)} \right)^{\frac{1}{\alpha L}} \tag{7}$$

is related to the code parameters, the propagation exponent and the performance constraint.

For a given R, the network throughput, normalized by the system bandwidth, is defined as

$$\tau(\lambda) = \lambda \cdot \nu(\lambda) \cdot \frac{r_{\text{M}} r_{\text{c}}}{M}, \tag{8}$$

where r_{M} is the rate of the MIMO scheme and r_{c} the rate of the convolutional code. For a given λ, the information efficiency is

$$\eta(R) = R \cdot \nu(R) \cdot \frac{r_{\text{M}} r_{\text{c}}}{M}. \tag{9}$$

Similarly to [6], for a given modulation order, the transmission capacity, λ_ϵ, is defined as the maximum λ such that $P_F = \epsilon$ is satisfied, i.e.

$$\lambda_\epsilon = \frac{M}{\pi R^2} \frac{\alpha^{-1} B(N-\alpha,\alpha)^{-1}}{m^\alpha} \left(\frac{d_s^2 K}{6} \right)^\alpha. \tag{10}$$

Note that $\lambda_\epsilon \propto M\epsilon^{1/L}$. As observed in [8], there is a linear dependence between λ_ϵ and M. However, the exponent $1/L$ of ϵ indicates a gain compared to the uncoded case, which increases with the diversity order of the code . This gain is a manifestation of the interference diversity achieved through FH and coding [6].

4.3 Optimization

A lower bound on $\tau(\lambda)$ and $\eta(R)$ is obtained by ommitting the unity inside the logarithm in (6). The maxima of these lower bounds, over λ and R, respectively, are

[6] This result is derived based on the assumption that independent interference powers are encountered across the decoder error events, which is not unreasonable for small values of λ_{eff} [22].

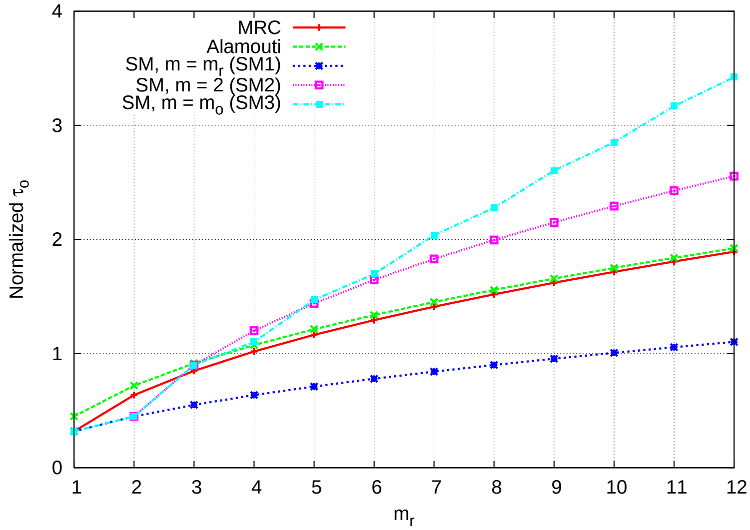

Fig. 4. Normalized τ_o vs. m_r for different MIMO schemes ($\alpha = 1/2$).

$$\tau_o = \frac{K^\alpha r_\mathrm{c} r_\mathrm{M}}{\pi R^2 \alpha^2 \mathrm{e} \ln 2} \cdot \frac{B(N-\alpha,\alpha)^{-1}}{m^\alpha} = K' r_\mathrm{M} \cdot \frac{B(N-\alpha,\alpha)^{-1}}{m^\alpha} \tag{11}$$

$$\eta_o = \frac{2K^{\alpha/2} r_\mathrm{c} r_\mathrm{M}}{\sqrt{M\lambda\pi}\alpha^{3/2} \mathrm{e} \ln 2} \cdot \frac{B(N-\alpha,\alpha)^{-1/2}}{m^{\alpha/2}} = K'' r_\mathrm{M} \cdot \frac{B(N-\alpha,\alpha)^{-1/2}}{m^{\alpha/2}}, \tag{12}$$

where K' and K'' are appropriately defined. If SM is the chosen MIMO technique, then $r_\mathrm{M} = m$, and τ_o and η_o can be further optimized with respect to m. Using the approximation in (5), we can easily find that the optimum number of streams, in the sense of maximizing $\tau_o(m)$ and $\eta(m)$, are

$$m_{o,\tau} = \min\left\{\left\lceil (1-\alpha)(m_r+1)\right\rfloor, m_t\right\} \tag{13}$$

$$m_{o,\eta} = \min\left\{\left\lceil (1-\alpha/2)(m_r+1)\right\rfloor, m_t\right\}. \tag{14}$$

In Fig.4 , τ_o/K is plotted vs. the number of RX antennas m_r for the following MIMO scenarios: $1 \times m_r$ MRC, $2 \times m_r$ Alamouti STBC and $m_r \times m_r$ SM, where $m = m_r, 2, m_o$ streams are activated (denoted SM1, SM2 and SM3, respectively, for ease of exposition). The lowest τ_o is achieved by activating all streams (SM3). The Alamouti code only slightly outperforms MRC, which is anticipated, since $(2m_r/2)^\alpha = m_r{}^\alpha$; the Alamouti code achieves twice the spatial diversity of MRC but introduces twice as much interference into the network due to the two independently transmitted streams. Fig.4 also shows us that diversity techniques are preferable for small m_r; as m_r increases, transmitting a number of independent streams pays off. The fact that SM3 underlies SM2 at $m_r = 4$ is attributed to the inaccuracy of (5), for small N.

In Fig.5, η_o/K'' is plotted vs. m_r. In contrast to the network throughput, activating all streams achieves higher information efficiency by the diversity techniques. Due to the exponent $\alpha/2$ of m in (12), the increase of m and thus

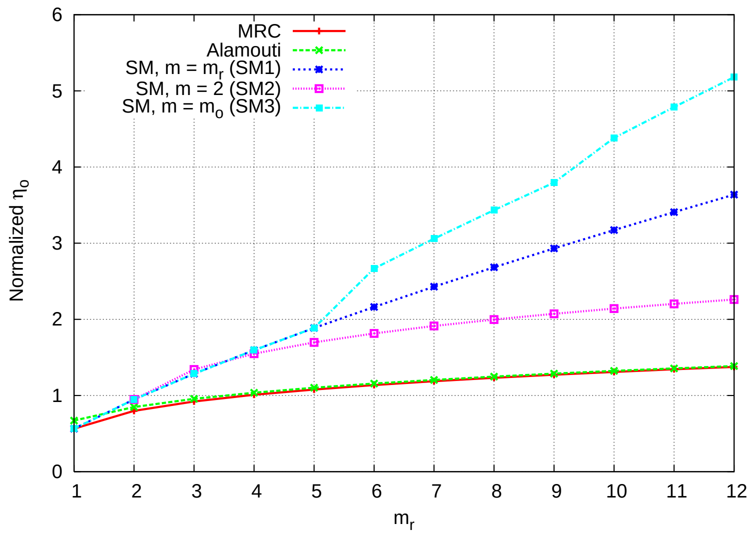

Fig. 5. Normalized η_o vs. m_r for different MIMO schemes ($\alpha = 1/2$).

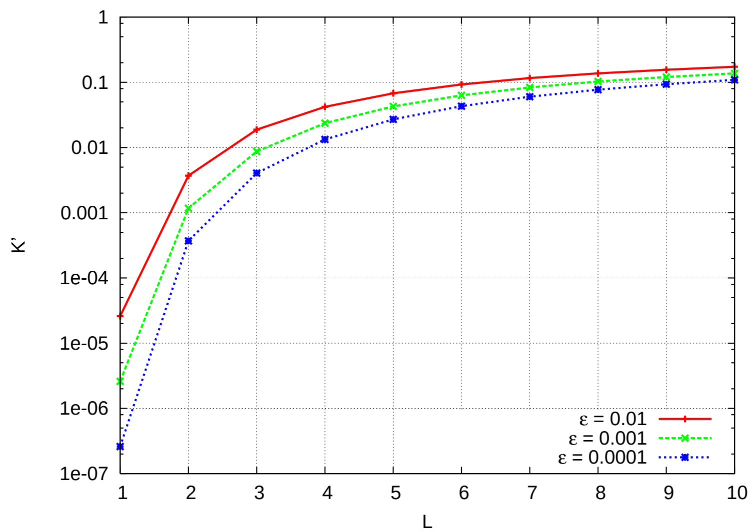

Fig. 6. K' vs. L for different ϵ ($L_i = 500, d_L = 1, R = 1, \alpha = 1/2, r_c = 1/2$).

the interference power is more than compensated for by the m-fold increase in rate, achieved by the SM schemes. As shown though by the gap between SM1 and SM3 curves, there is still a gain to be had if some of the streams are suppressed.

Fig.6 presents the dependence of the multiplicative factor K' on the code diversity order L for different FEP constraints ϵ. The number of information bits is $L_i = 500$, so, for a rate $r_c = 1/2$ code, this implies that the packet size is 1000 bits. Note that the gain in terms of network throughput compared to the uncoded case ($L = 1$) is substantial and most of it is obtained for relatively low L, i.e. moderate complexity.

5 Concluding remarks

We have presented an overview of existing work on the performance analysis of ad hoc networks based on the Poisson random field model for the distribution of TXs in space. The advantage of the framework is that it allows the analytical evaluation of various channel models and physical layer techniques in terms of network performance. In this manner, general design guidelines can be obtained prior to more detailed and time consumming network simulations. A special section in the paper was devoted to an analysis of a FH-MA physical layer combined with various MIMO techniques.

In most of the scenarios studied, the links are assumed to act in an uncoordinated manner. In [12], the advantages of a simple guard-zone scheduling scheme were demonstrated in a DS-CDMA setting. It remains an open question what other forms of scheduling, cooperation and MAC protocols between nodes can be analyzed using the Poisson stochastic model. The analysis of multi-user techniques, such as successive interference cancellation presented in [7], is also a challenging topic, especially when the nodes are equipped with multiple antennas. A number of multi-user MIMO techniques are well studied for the MA and broadcast channels [23] and it remains to be seen how these results can be incorporated in the ad hoc network setting.

As we saw in section 4, the choice of MIMO technique was dictated by the network metric. The problem lies in the fact that both the network throughput and the information efficiency are metrics defined for a single-hop network, albeit with a multi-hop network in mind. A more accurate metric for a multi-hop network is the *density of progress* [24], defined as the mean total distance travelled in one hop by all transmission within a unit area. The density of progress is determined in [24] for a random access MAC protocol and a routing strategy wherein the next-hop RX is selected based on the expected forward progress. It is of interest to use this metric, or similar "multi-hop" metrics, in order to evaluate physical layer techniques, combined with MAC and routing protocols. Some steps to this direction are taken in [22], where the density of progress is computed for the MIMO techniques presented in this paper.

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