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Research Article

Effect of Node Mobility on MU-MIMO Transmissions in Mobile Ad Hoc Networks

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In this paper, we investigate the expected outage probability and expected throughput of a multi-user multiple-input multiple-output (MU-MIMO) transmission in mobile ad hoc networks (MANET) in the presence of co-channel interference and unpredictable inter-beam interference. In order to achieve multi-user diversity gain, the receiving nodes are required to report measured channel information to the transmitting node. During the time gap between channel measurement and data transmission, the channel may change with the location of moving nodes. The unpredictable behavior may cause a mismatch between the weight of beams and the instantaneous channel and the inter-beam interference in the data transmission phase. In order to obtain the closed form expected outage probability, we categorize the behavior of nodes according to whether the inter-beam interference exists or not and the number of received interference beams. The probability of each category and the closed form outage probability of an instantaneous MU-MIMO transmission of each category are derived. Additionally, the expected throughput of an MU-MIMO transmission which changes with the number of receiving nodes is obtained, and the optimal value of receiving nodes to maximize the expected throughput is discussed. Numeric results show the unpredictable inter-beam interference degrades the outage probability performance. Reducing the duration of the time gap could improve the expected outage probability and expected throughput.

1. Introduction

The diversity of applications gives rise to the requirement on the flexibility of wireless networks. A conventional cellular network or wireless local area network (WLAN) supplies the inability to satisfy the requirements. Due to the agility network structure, MANET has attracted a lot of attention in different application areas, such as military battlefield [1], postdisaster reconstruction [2], emergency mission, and vehicular communication [3].

A MANET is composed of a collection of mobile nodes equipped with a wireless transceiver. The nodes communicate with each other directly or by multihop link with the help of intermediate nodes [4]. Because of the lack of coordination of infrastructure or central node, multiple transmissions may occur on the same channel simultaneously and interfere with each other. Inevitably, the co-channel interference impairs the performance of transmissions. In prior works, the transmission performance in the presence of co-channel interference was investigated [5, 6], and some interference coordination schemes were proposed [7–9].

In order to reduce co-channel interference and improve the aggregate throughput of MANET, multiple-input multiple-output (MIMO) has been exploited by many researchers [10–12]. Especially, MU-MIMO, due to its extremely high spectral efficiency, receives a significant attention [13–16]. In the 3rd Generation Partnership Project (3GPP) long term evolution-advanced (LTE-A) [17] and IEEE 802.11 ac [18], the MU-MIMO is adopted. An MU-MIMO transmission is performed in two phases: beam selection phase and data transmission phase. In the beam selection phase, the transmitting node selects a set of orthogonal beams according to the reported channel measurement information from candidate receiving nodes. In the data transmission phase, the transmitting node delivers data packets on the same channel to receiving nodes simultaneously, using the selected orthogonal beams.

The orthogonal beams are proven to maximize the received SINR of a receiving node. However, achieving the performance requires the matching between the weight of a beam and instantaneous wireless channel. As shown in Figure 1, a time gap for reporting channel measurement information is inevitable in the beam selection phase, whose duration is related to the number of the candidate receiving nodes. Due to the randomness of nodes' movement, the behavior of nodes is unpredictable during the time gap. If a node moves randomly during the time gap, the wireless channel between the moving node and the transmitting node or a receiving node changes with the location of the moving node. In the data transmission phase, the instantaneous wireless channel mismatches with the weight of beams derived from measured channel information. As a result, the beams for each receiving node may interfere with each other. The unpredicted inter-beam interference will degrade the performance of an MU-MIMO transmission. In previous work [13], the influence of the inter-beam interference on the outage probability performance was exploited, but the randomness of interference was not taken into account.

The expected throughput of an MU-MIMO transmission is the sum of the expected throughput of each receiving node. Intuitively, the increase of receiving nodes could bring more expected throughput of an MU-MIMO transmission. However, with the increase of receiving nodes, the probability of that multiple nodes keep motionless simultaneous during the time gap decreases, but the probability of inter-beam interference increases. Moreover, the increase of receiving nodes reduces the power of the desired signal and potentially increases the power of inter-beam interference. For a receiving node, the instantaneous received SINR and the expected throughput are reduced. Therefore, the expected throughput of an MU-MIMO transmission may not be improved with the increase of receiving nodes. How to balance the expected throughput and the number of receiving nodes is worth discussing.

Motivated by the discussion above, in the paper, we investigate the outage probability performance and expected throughput of an MU-MIMO transmission in MANET in the presence of co-channel interference and unpredictable inter-beam interference. Summarily, our main contributions are given as follows:

(i) We categorize the mobility behavior of nodes according to whether the inter-beam interference exists or not and the number of received interference beams. The probability of each category is derived.

(ii) We derive the closed form outage probability of an instantaneous MU-MIMO transmission considering the co-channel interference and unpredictable inter-beam interference.

(iii) We explore the expected throughput of an MU-MIMO transmission and discuss the optimal number of receiving nodes to maximize the expected throughput.

The remainder of the paper is structured as follows. Section 2 gives the system model. Section 3 derives the instantaneous and expected outage probability of an MU-MIMO transmission in the presence of co-channel interference and unpredictable inter-beam interference. Section 4 explores the expected throughput of an MU-MIMO transmission and discusses the optimal number of receiving nodes to maximize the expected throughput. Section 5 describes the numeric results. Finally, Section 6 gives the conclusions.

2. System Model

We assume a MANET consisting of a collection of half-duplex nodes adopts slotted ALOHA protocol [19] and MU-MIMO transmissions. In each slot, a subset of nodes transmits data on the same channel, with the same transmit power P_t. Considering the nodes in MANET are placed arbitrarily, the transmitting nodes in each slot are assumed to be distributed according to a Spatial Poisson Point Process (SPPP) with intensity λ [20]. The model has been used and the validity has been confirmed in prior works. Hence, the set of transmitting nodes is denoted as $\Phi(\lambda) = \{Z_i\}$, where Z_i is the position of transmitting node i at some time instant.

In the beam selection phase of an MU-MIMO transmission, the transmitting node equipped with N_t transmit antennas selects $K(1 < K \le N_t)$ orthogonal beams using reported channel information. In the data transmission phase, the transmitting node delivers data packets to K receiving nodes equipped with a single receive antenna simultaneously, using orthogonal beams $\mathbf{w}_k (k = 1, 2, \cdots, K)$, where $\mathbf{w}_k$ satisfies $\mathbf{w}_k^{\mathrm{H}}\mathbf{w}_k = 1$ and $\mathbf{w}_k^{\mathrm{H}}\mathbf{w}_l = 0 (k \ne l)$.We assume the duration of the time gap is T_{gap}, and the wireless channel does not change with time within the time gap. At the start time of the time gap, the nodes in an MU-MIMO system are assumed to be motionless with a probability p_{state}. After a time interval t, each node changes to the opposite state independently, i.e., the motionless node becomes moving or vice versa. We assume the number of state change in a period of time obeys a Poisson distribution. Hence, the time interval t follows an exponential distribution with mean $1/\theta$, i.e.,

$$f(t) = \theta e^{-\theta t}, t > 0. \tag{1}$$

Further, we assume a node moves in a very short time could result in an obvious variation of location, and the instantaneous wireless channel changes with the location.

3. Outage Probability Evaluation

We assume a receiving node k locates at the origin. In the data transmission phase, the received signal of the receiving node k is denoted as

$$y_k = \underbrace{\sqrt{\frac{P_t}{K} D_k^{-\alpha}}\mathbf{h}_k^H \mathbf{w}_k \mathbf{s}_k}_{\text{Desired Signal}} + \underbrace{\sum\nolimits_{j \in K, j \ne k} \sqrt{\frac{P_t}{K} D_k^{-\alpha}}\mathbf{h}_k^H \mathbf{w}_j \mathbf{s}_j}_{\text{Inter-beam Interference Signal}} + \underbrace{\sum\nolimits_{\varphi \in \Phi/T_k} \sqrt{P_t |Z_\varphi|^{-\alpha}} g_{\varphi,k} s_\varphi}_{\text{Co-channel Interference Signal}} + n_k, \tag{2}$$

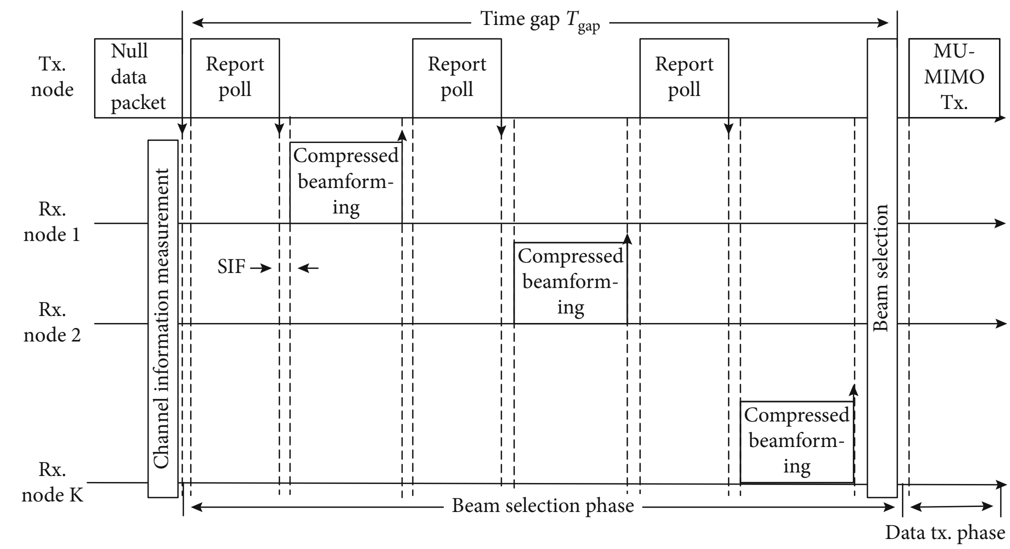

Figure 1: MU-MIMO beamforming model.

where $\mathbf{h}_k \in \mathbb{C}^{N_t \times 1}$ is the channel gain vector between the receiving node k and the transmitting node T_k, whose entries follow complex Gaussian distribution $h_{i,k} \sim \mathscr{C}\mathscr{N}(0,1)$. Similarly, $g_{\varphi,k} \in \mathbb{C}^{1\times 1}$ represents the channel gain between the receiving node k and another transmitting node φ. $\mathbf{s}_k \in \mathbb{C}^{K\times 1}$ is the symbol vector transmitted from the transmitting node. Additionally, n_k represents the additive white Gaussian noise (AWGN) with zero mean and variance of σ^2.

For the receiving node k, whether the inter-beam interference signal exists or not depends on whether the wireless channels change with the location of nodes during the time gap or not. In case all nodes keep motionless during the time gap, the orthogonality of beams could be achieved, and the inter-beam interference is eliminated. In case the transmitting node moves during the time gap, the beams for all receiving nodes interfere with each other. Otherwise, the beam for a motionless receiving node is interfered with the beams for the moving receiving nodes, but the beam for a moving receiving node is interfered with the other beams. With the goal of evaluating the performance of an MU-MIMO transmission, the behavior of nodes is categorized according to whether the inter-beam interference exists or not and the number of received interference beams. In order to simplify the calculations, we define several events to depict the behavior of nodes as follows.When the event E_2 or the event E_3 with $M = K$ occurs, the beam for a receiving node is interfered with the beams for $K-1$ receiving nodes. When the event E_3 with $0 < M < K$ occurs, the beam for a motionless receiving node is interfered with the beams for M moving receiving nodes, but the beam of a moving receiving node is interfered with the beams for $K-1$ receiving nodes. With this in mind, we further define the measurement of instantaneous received SINR for motionless and moving receiving nodes as event E_3^s and E_3^m, respectively.

Definition 1. An event that the transmitting node and the receiving nodes of an MU-MIMO system both keep motionless during the time gap is denoted as event E_1.

Definition 2. An event that the transmitting node moves during the time gap, independent of the states of the receiving nodes, is denoted as event E_2.

Definition 3. An event that the transmitting node is motionless but $M(1 < M \le K)$ receiving nodes move during the time gap is denoted as event E_3.

The outage probability of an MU-MIMO transmission is defined as the probability that instantaneous received SINR does not exceed the required SINR threshold. The expected outage probability is the sum of outage probability weighted by the probability of defined events. Assuming the required SINR threshold is γ_{thre}, hence, the expected outage probability is expressed as

$$p_k^{\exp}(\gamma_{\text{thre}}) = \sum_{i=1}^{3} \mathbb{P}(E_i)\mathbb{P}\left(\gamma_{k,E_i}^{\text{ins}} \le \gamma_{\text{thre}}\right) = \sum_{i=1}^{2} \mathbb{P}(E_i)\mathbb{P}\left(\gamma_{k,E_i}^{\text{ins}} \le \gamma_{\text{thre}}\right) + \mathbb{P}(E_3) \times \left[\mathbb{P}(E_3^s)\mathbb{P}\left(\gamma_{k,E_3^s}^{\text{ins}} \le \gamma_{\text{thre}}\right) + \mathbb{P}(E_3^m)\mathbb{P}\left(\gamma_{k,E_3^m}^{\text{ins}} \le \gamma_{\text{thre}}\right)\right], \quad (3)$$

where $\mathbb{P}(E_i)$ is the probability of event E_i and $\gamma_{k,E_i}^{\text{ins}}$ represents the instantaneous received SINR of the receiving node k when the event E_i occurs.

3.1. Probability of the Events. In terms of Definition 1, the event E_1 means that all nodes are motionless at the start time of the time gap and keep motionless during a time interval not less than T_{gap}. Using the probability density function (PDF) in equation (1), the probability of event E_1 is denoted as

$$\mathbb{P}(E_1) = \left(p_{\text{state}} \int_{T_{\text{gap}}}^{\infty} \theta e^{-\theta t} dt\right)^{K+1} = \left(p_{\text{state}} e^{-\theta T_{\text{gap}}}\right)^{K+1}. \quad (4)$$

When the event E_2 occurs, no matter whether the receiving nodes move or not, the transmitting node is moved during the time gap. Hence, the probability of event E_2 is denoted as

$$\mathbb{P}(E_2) = \frac{1}{K+1} \cdot \left(1 - p_{\text{state}} \int_{T_{\text{gap}}}^{\infty} \theta e^{-\theta t} dt\right) = \frac{1}{K+1} \cdot \left(1 - p_{\text{state}} e^{-\theta T_{\text{gap}}}\right). \quad (5)$$

As described in Definition 3, the transmitting node and $K-M$ receiving nodes are motionless at the start time of the time gap and keep motionless within a time interval not less than T_{gap}. But $M(0 < M \le K)$ receiving nodes move during the time gap. Hence, the probability of event E_3 is denoted as

$$\begin{aligned}\mathbb{P}(E_3) &= \left(p_{\text{state}} \int_{T_{\text{gap}}}^{\infty} \theta e^{-\theta t} dt\right)^{K-M+1} \left(1 - p_{\text{state}} \int_{T_{\text{gap}}}^{\infty} \theta e^{-\theta t} dt\right)^{M} \\ &= \left(p_{\text{state}} e^{-\theta T_{\text{gap}}}\right)^{K-M+1} \left(1 - p_{\text{state}} e^{-\theta T_{\text{gap}}}\right)^{M}. \end{aligned} \quad (6)$$

Furthermore, the probabilities of event E_3^s and E_3^m are $\mathbb{P}(E_3^s) = 1 - M/K$ and $\mathbb{P}(E_3^m) = M/K$, respectively.

3.2. Outage Probability of Instantaneous MU-MIMO Transmission. In an MU-MIMO transmission, the instantaneous received SINR of the receiving node k is denoted as

$$\gamma_k^{\text{ins}} = \frac{(P_t/K) D_k^{-\alpha} \left|\mathbf{h}_k^H \mathbf{w}_k\right|^2}{\sigma^2 + \phi \sum_{j \in U} (P_t/K) D_k^{-\alpha} \left|\mathbf{h}_k^H \mathbf{w}_j\right|^2 + \sum_{\varphi \in \Phi/T_k} P_t \left|Z_\varphi\right|^{-\alpha} \left|g_{\varphi,k}\right|^2}, \quad (7)$$

where $U = M$ if receiving node k is a motionless node, or $U = K-1$ if receiving node k is a moving node.

For defined events above, the instantaneous received SINRs could be obtained from γ_k^{ins} by setting $\phi = 0$ or $\phi = 1$.

(i) When $\phi = 0$, the instantaneous received SINR $\gamma_k^{\text{ins}} = \gamma_{k,E_1}^{\text{ins}}$

(ii) When $\phi = 1$ and $0 < M < K$, the instantaneous received SINR $\gamma_k^{\text{ins}} = \gamma_{k,E_3^s}^{\text{ins}}$

(iii) When $\phi = 1$ and $M = K$, the instantaneous received SINR $\gamma_k^{\text{ins}} = \gamma_{k,E_2}^{\text{ins}} = \gamma_{k,E_3^m}^{\text{ins}}$

Neglecting the effect of AWGN in the interference-limit system for analytical simplicity, the outage probability of an instantaneous MU-MIMO transmission is denoted as

$$\begin{aligned} p_k^{\text{ins}}(\gamma_{\text{thre}}) &= \mathbb{P}\left(\gamma_k^{\text{ins}} \le \gamma_{\text{thre}}\right) = \mathbb{P}\left(S_k \le (\phi \rho I_{k,\text{IBI}} + I_{k,CCI}) \frac{\gamma_{\text{thre}}}{\rho}\right) \\ &= \int_0^\infty \mathbb{P}(S_k \le \omega x) f_{\phi \rho I_{k,\text{IBI}} + I_{k,\text{CCI}}}(x) dx, \end{aligned} \quad (8)$$

where $\rho = 1/K D_k^\alpha$ and $\omega = \gamma_{\text{thre}}/\rho$. $S_k = \left|\mathbf{h}_k^H \mathbf{w}_k\right|^2$ and $I_{k,\text{IBI}} = \sum_{j \in U} \left|\mathbf{h}_k^H \mathbf{w}_j\right|^2$ represent chi-squared random variables with 2 $(N_t - K + 1)$ and $2U$ degrees of freedom, respectively. Using the PDF of chi-squared random variable S_k with $2(N_t - K + 1)$ degrees of freedom, the term $\mathbb{P}(S_k \le \omega x)$ is derived as

$$\begin{aligned} \mathbb{P}(S_k \le \omega x) &= \int_0^{\omega x} \frac{t^{N_t - K}}{2^{N_t - K + 1} (N_t - K)!} e^{-t/2} dt \\ &= 1 - \frac{1}{(N_t - K)!} \Gamma(N_t - K + 1, \omega x) \\ &= 1 - e^{-\omega x} \sum_{m=0}^{N_t - K} \frac{(\omega x)^m}{m!}, \end{aligned} \quad (9)$$

where $\Gamma(q, x) = \int_x^\infty t^{q-1} e^{-t} dt = (q-1)! e^{-x} \sum_{m=0}^{q-1} x^m / m!$ is complementary incomplete Gamma function with $q > 0$. Inserting the result into equation (8), the outage probability is expressed as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \int_0^\infty \sum_{m=0}^{N_t - K} \frac{(\omega x)^m}{m!} e^{-\omega x} f_{\phi \rho I_{k,\text{IBI}} + I_{k,\text{CCI}}}(x) dx. \quad (10)$$

3.2.1. Outage Probability when $\phi = 0$. In case $\phi = 0$, the effect of inter-beam interference is eliminated. The outage probability in equation (10) is rewritten as

$$\begin{aligned} p_k^{\text{ins}}(\gamma_{\text{thre}}) &= 1 - \int_0^\infty \sum_{m=0}^{N_t - K} \frac{(\omega s)^m}{m!} e^{-\omega x} f_{I_{k,\text{CCI}}}(x) dx \\ &= 1 - \sum_{m=0}^{N_t - K} \frac{(-\omega)^m}{m!} \frac{d^m}{d\omega^m} \mathscr{L}_{I_{k,\text{CCI}}}(\omega), \end{aligned} \quad (11)$$

where $\mathscr{L}_{I_{k,\text{CCI}}}(\omega)$ is the Laplace transform of $I_{k,\text{CCI}}$. The transform of $\mathscr{L}[t^m f(t)] = (-1)^m F^{(m)}(s)$ is employed and $F^{(m)}(s)$ is the mth order differential of the Laplace transform of $f(t)$. Note that when $K = N_t$, the outage probability is simplified as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \mathscr{L}_{I_{k,\text{CCI}}}(\omega). \quad (12)$$

According to the system model, the transmitting nodes in each slot are distributed according to an SPPP with intensity λ. Consequently, the co-channel interference could be modeled as a general Poisson shot noise process [21]. The Laplace transform of random variable $I_{k,\text{CCI}}$ is given as

$$\begin{aligned} \mathscr{L}_{I_{k,\text{CCI}}}(\omega) &= \exp\left\{-\lambda \int_{\mathbb{R}^2} 1 - E_H\left[\exp\left(-\omega H |x|^{-\alpha}\right)\right]\right\} \\ &= \exp\left\{-2\pi\lambda \int_0^\infty \frac{x}{1 + |x|^\alpha/\omega} dx\right\} = \exp\left(-\lambda Q \omega^\delta\right), \end{aligned} \quad (13)$$

where $\delta = 2/\alpha$ and $Q = \pi \Gamma(\delta) \Gamma(1-\delta)$. Especially, in case $\alpha = 4$, we have $Q = \pi^2$. Hence, when $K = N_t$, the outage probability is expressed as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \exp\left(-\lambda Q \omega^{\delta}\right). \tag{14}$$

In order to achieve a high probability of successful reception, it is reasonable that a very strict quality of service (QoS) is required, resulting in that the density of transmitting nodes λ shall be very small. Consequently, the mth order differential of $\mathscr{L}_{I_{k,\text{CCI}}}(\omega)$ could be evaluated using the first-order Taylor series around $\lambda Q\omega^{\delta} = 0$. For all $m \geq 1$, the mth order differential of $\mathscr{L}_{I_{k,CCI}}(\omega)$ is given approximately as

$$\frac{d^m}{d\omega^m}\mathscr{L}_{I_{k,\text{CCI}}}(\omega) \approx -\left(\lambda Q\omega^{\delta-m}\prod_{l=0}^{m-1}(\delta - m)\right)e^{-\lambda Q\omega^{\delta}} + \Psi\left(\lambda^2 Q^2 \omega^{2\delta}\right). \tag{15}$$

In case $K < N_t$, combining the equation (11) with (15) and discarding the term $\Psi(\lambda^2 Q^2 \omega^{2\delta})$, the outage probability of an instantaneous transmission when the event E_1 occurs is derived as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = \lambda Q \omega^{2/\alpha}\left(1 + \sum_{m=1}^{N_t-K}\frac{1}{m!}\prod_{l=0}^{m-1}(m-\delta)\right). \tag{16}$$

3.2.2. Outage Probability when $\phi = 1$. In this section, in order to simplify the derivation of outage probability, we first give a definition and a proposition as follows [22].

Definition 4. Given a Beta distributed random variable X with two positive shape parameters a and b, its cumulative distribution function (CDF) is a regularized incomplete beta function, denoted as

$$\begin{aligned}\mathscr{F}_x(a,b) = \mathbb{P}(X \leq x) &= 1 - \sum_{i=1}^{a}\frac{\Gamma(b+i-1)}{\Gamma(b)\Gamma(i)}x^{i-1}(1-x)^b \\ &= \sum_{i=1}^{b}\frac{\Gamma(a+i-1)}{\Gamma(a)\Gamma(i)}x^a(1-x)^{i-1},\end{aligned} \tag{17}$$

where $\Gamma(q) = \int_0^{\infty} t^{q-1}e^{-t}\text{d}t$ is the Gamma function.

Proposition 1. *For any $x \geq 0$, and nonnegative integers n, v, and r where $n \geq r$,*

$$\sum_{l=0}^{n-r}\left(\frac{x}{1+x}\right)^l\binom{v+l-1}{l} = (1+x)^v \mathscr{F}_{1/1+x}(v, n-r+1). \tag{18}$$

In case $\phi = 1$, the performance of MU-MIMO transmission is limited by inter-beam interference and co-channel interference simultaneously. The outage probability in equation (10) is rewritten as

Table 1: Simulation configurations.

Parameter	Value
Total power of transmitting node P_t	23 dBm
Transmit antenna N_t	8
Receive antenna N_r	1
Receiving nodes K	4,8
Mobile receiving nodes M	1, $K/2$, K
Path loss exponent α	4
SINR threshold γ_{thre}	-30 dB
Distance between Tx and Rx D_k	100 m
Distribution density of nodes λ	10~100/km^2
Probability of motionless state p_{state}	0.5
Average time interval θ	1 s
Number of discrete rates L	4

$$\begin{aligned}p_k^{\text{ins}}(\gamma_{\text{thre}}) &= 1 - \int_0^{\infty}\sum_{m=0}^{N_t-K}\frac{(\omega x)^m}{m!}e^{-\omega x}f_{\rho I_{k,\text{IBI}}+I_{k,\text{CCI}}}(x)dx \\ &= 1 - \sum_{m=0}^{N_t-K}\frac{(-\omega)^m}{m!}\frac{d^m}{d\omega^m}\mathscr{L}_{\rho I_{k,IBI}}(\omega)\mathscr{L}_{I_{k,\text{CCI}}}(\omega).\end{aligned} \tag{19}$$

When $K = N_t$, the outage probability is simplified as $p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \mathscr{L}_{\rho I_{k,\text{IBI}}}(\omega)\mathscr{L}_{I_{k,\text{CCI}}}(\omega)$. Otherwise, the outage probability is further denoted as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \sum_{m=0}^{N_t-K}\frac{(-\omega)^m}{m!}\sum_{l=0}^{m}\frac{d^l}{d\omega^l}\mathscr{L}_{\rho I_{k,\text{IBI}}}(\omega)\frac{d^{m-l}}{d\omega^{m-l}}\mathscr{L}_{I_{k,\text{CCI}}}(\omega). \tag{20}$$

Note that $\mathscr{L}_{I_{k,\text{CCI}}}(\omega)$ and its mth order differential were derived in equations (13) and (14). Using the PDF of a chi-squared random variable $I_{k,\text{IBI}}$ with $2U$ degrees of freedom, the Laplace transform $\mathscr{L}_{I_{k,\text{IBI}}}(\omega)$ and its mth order differential are, respectively, denoted as

$$\mathscr{L}_{I_{k,\text{IBI}}}(\omega) = \frac{1}{(1+2\rho\omega)^U}, \tag{21}$$

$$\frac{d^m}{d\omega^m}\mathscr{L}_{I_{k,\text{IBI}}}(\omega) = \frac{(-2\rho)^m}{(1+2\rho\omega)^{U+m}}\prod_{j=0}^{m-1}(U+j). \tag{22}$$

Hence, when $K = N_t$, the outage probability is expressed as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = 1 - \frac{e^{-\lambda Q\omega^{\delta}}}{(1+2\rho\omega)^U}. \tag{23}$$

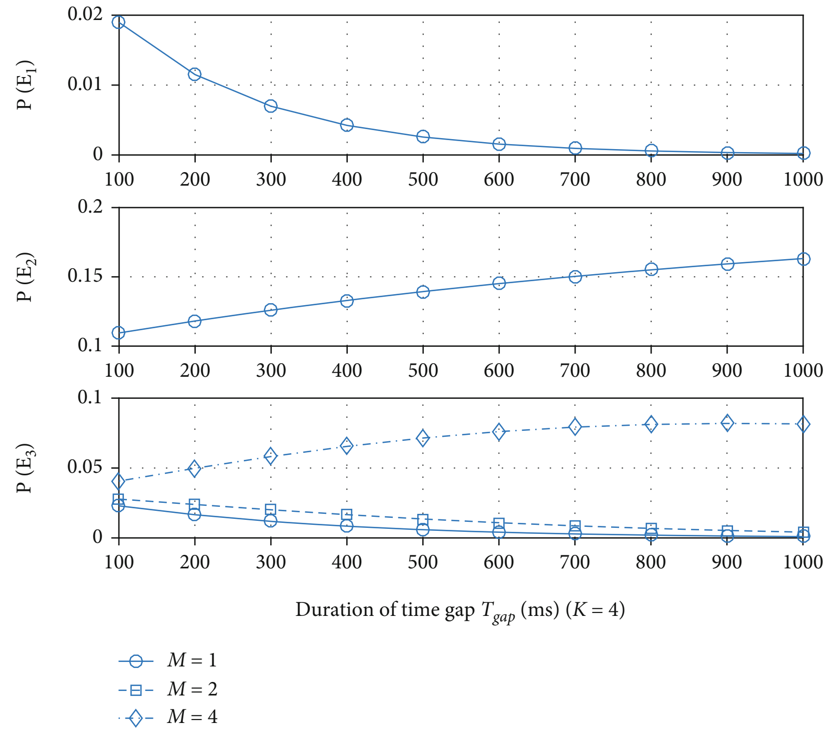

FIGURE 2: Probability of events vs. duration of time gap.

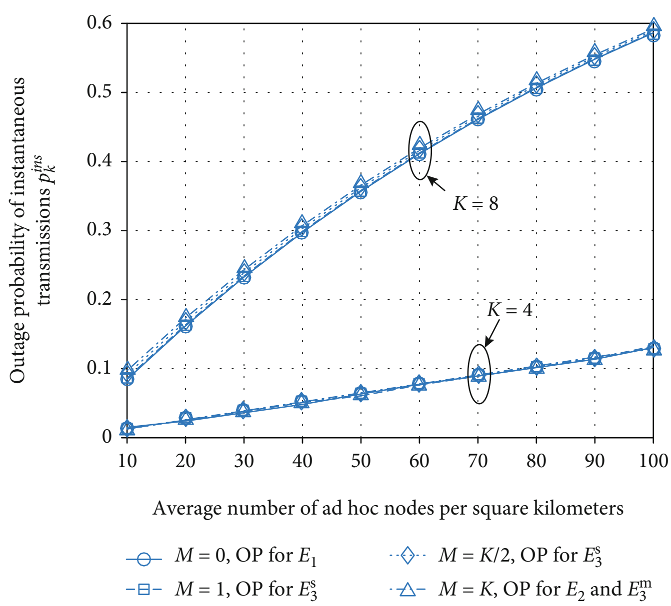

FIGURE 3: Outage probability of instantaneous MU-MIMO transmissions vs. average number of ad hoc nodes.

In case $K < N_t$, the outage probability could be obtained by combing equation (19) with the results in equations (15) and (22). With the goal of simplifying the expression, we use Definition 4 and Proposition 1 above and perform the first-order Taylor series around $\lambda Q \omega^{\delta} = 0$ with discarding the term $\Psi(\lambda^2 Q^2 \omega^{2\delta})$. As a result, the outage probability of an instantaneous transmission is denoted as

$$p_k^{\text{ins}}(\gamma_{\text{thre}}) = \mathcal{F}_{2\gamma_{\text{thre}}/1+2\gamma_{\text{thre}}}(N_t - K + 1, U) + \lambda Q \omega^{2/\alpha} \cdot \left(\mathcal{K}(U) - \mathcal{F}_{2\gamma_{\text{thre}}/1+2\gamma_{\text{thre}}}(N_t - K + 1, U)\right), \quad (24)$$

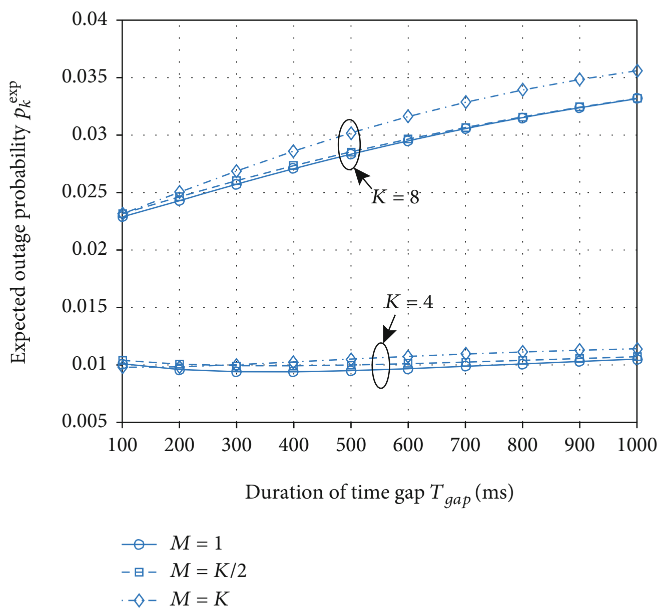

FIGURE 4: Expected outage probability of MU-MIMO transmissions vs. duration of time gap.

where $\mathscr{K}(U) = 1 + \sum_{m=0}^{N_t-K-1} \binom{U+m-1}{m} (2\gamma_{\text{thre}}/1+2\gamma_{\text{thre}})^m \sum_{i=1}^{N_t-m-1}(1/i!)\prod_{j=0}^{i-1}(j-\delta)$.

The outage probability could be obtained with $U = M$ when the event E_3^s occurs, or with $U = K-1$ when the event E_2 or E_3^m occurs.

4. Throughput of MU-MIMO Transmission

Assume adaptive N-QAM modulation with L discrete rates is applied in an MU-MIMO transmission. When an event E_i occurs, if the instantaneous received SINR lies in $[\Gamma_l, \Gamma_{l+1})(1 \le l \le L)$, the instantaneous rate is given as

$$b_l = \log_2\left(1 + \frac{\Gamma_l}{G}\right) \text{bps/Hz}, \ \gamma_{k,E_i}^{\text{ins}} \in [\Gamma_l, \Gamma_{l+1}), \tag{25}$$

where G is Shannon Gap with variable rate N-QAM transmission [23]. Hence, the long-term expected throughput of receiving node k when the event E_i occurs is denoted as

$$\begin{aligned} C_{k,E_i}^{\exp} &= \sum_{l=1}^{L-1} l \cdot \mathbb{P}\left(\Gamma_l \le \gamma_{k,E_i}^{\text{ins}} < \Gamma_{l+1}\right) + L \cdot \mathbb{P}\left(\gamma_{k,E_i}^{\text{ins}} \ge \Gamma_L\right) \\ &= \sum_{l=1}^{L-1} l \cdot \left(p_{k,E_i}^{\text{ins}}(\Gamma_{l+1}) - p_{k,E_i}^{\text{ins}}(\Gamma_l)\right) + L \cdot \left(1 - p_{k,E_i}^{\text{ins}}(\Gamma_L)\right). \end{aligned} \tag{26}$$

The expected total throughput of an MU-MIMO transmission is given as

$$C_{\text{tot}}^{\exp} = \sum_{k=1}^{K}\left(\mathbb{P}(E_1)C_{k,E_1}^{\exp} + \mathbb{P}(E_2)C_{k,E_2}^{\exp} + \mathbb{P}(E_3)\left(\mathbb{P}(E_3^s)C_{k,E_3^s}^{\exp} + \mathbb{P}(E_3^m)C_{k,E_3^m}^{\exp}\right)\right). \tag{27}$$

Intuitively, the increase of receiving nodes could bring more expected total throughput. However, with the increase of the number of receiving nodes, the probability that multiple nodes keep motionless during the time gap decreases, causing the probability that the event E_1 or E_3 occurs decreases. In addition, the increase of receiving nodes reduces the power of the desired signal and potentially increases the power of inter-beam interference. For a receiving node, the instantaneous received SINR and the long-term expected throughput are reduced. Hence, there is an optimal number of receiving nodes K^* which could maximize the expected total throughput of an MU-MIMO transmission, i.e.,

$$K^* = \arg\max_{1<K\le N_t} C_{\text{tot}}^{\exp}. \tag{28}$$

5. Numeric Results

This section reports the results of computer simulations. In the simulation, the MANET nodes are assumed to be located randomly in a circle region with 1 km radius. The simulation configurations are listed in Table 1.

Figure 2 shows the probabilities of the defined events. With the increase of the duration of the time gap, the probability that all the nodes keep motionless decreases, i.e., the probability of the event E_1 decreases. But the probability that the transmitting node is moving increases, causing the increase of the probability of the event E_2. When the event

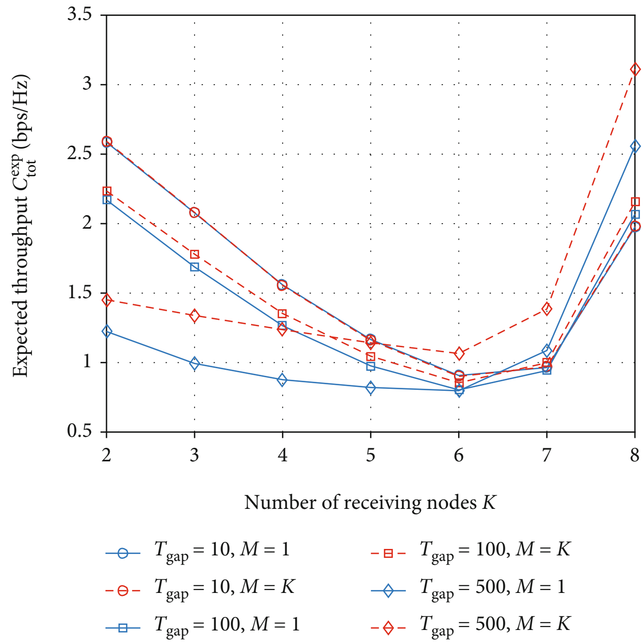

Figure 5: Expected throughput of MU-MIMO transmissions vs. number of receiving nodes.

E_3 occurs, the probability is dependent on the number of moving nodes. If the moving nodes are less than the receiving nodes, the probability that the motionless nodes keep the same state decreases; hence, the probability of the event E_3 decreases. Otherwise, the probability that all receiving nodes are moving increases with the duration of the time gap.

The outage probabilities of instantaneous MU-MIMO transmissions are given in Figure 3. On the one hand, with the increase of the intensity of the MANET nodes, a receiving node experiences more severe co-channel interference signals. On the other hand, the increasing receiving nodes reduce the power of the desired signal but enhance the power of inter-beam interference. As a result, the outage probabilities of instantaneous MU-MIMO transmissions increase with the intensity of the MANET nodes and the number of receiving nodes. Further, because of the moving receiving nodes in the event E_2 and E_3, i.e., $M > 0$, the receiving nodes will receive the inter-beam interference signal. Hence, the outage probabilities of the event E_2 and E_3 ($M > 0$) are higher than that of the event E_1 ($M = 0$). And the outage probability increase with the number of moving receiving nodes.

Figure 4 describes the relationship between the expected outage probability and the duration of the time gap. In terms of the definition of the events, the probability of the event E_1 decreases but the probabilities of the event E_2 and E_3 increase with the duration of the time gap. As a result, the expected outage probability increases with the probabilities of the event E_2 and E_3. However, the increase of the expected outage probability is related to the number of receiving nodes. For instance, the increase of $K = 8$ is faster than that of $K = 4$. On the other hand, with the increase of the number of moving receiving nodes, the probability of event E_3 and further the expected outage probability increase.

Figure 5 reflects the impact of the number of receiving nodes on the expected throughput of an MU-MIMO transmission. When the number of the receiving nodes is less than a threshold, the increasing receiving nodes reduce the expected throughput of each receiving node and the total expected throughput. While the number of receiving nodes excesses the threshold, the total expected throughput begins to grow with the increase of the receiving nodes. As a result, an optimal value of K equal to 2 or the number of the transmit antennas could maximize the total expected throughput. On the other hand, it is obvious that the increase of the duration of the time gap reduces the total expected throughput. In case of a fixed duration of the time gap, the total expected throughput increases with the number of moving receiving nodes.

6. Conclusions

This paper evaluates the expected outage probability and expected throughput of an MU-MIMO transmission in MANET in the presence of co-channel interference and unpredictable inter-beam interference. To derive the closed form results, the unpredictable behavior of nodes is categorized. Based on the categories, the closed form outage probability of instantaneous MU-MIMO transmissions and further expected outage probability are obtained. The analytical and numeric results indicate the unpredictable inter-beam interference degrades the outage probability performance. Reducing the duration of the time gap could improve the expected outage probability and expected throughput.

As a future work, we will explore the performance optimization by interference management or resource assignment based on the derived results. At the same time, we believe that the application of integrated cognition-control-communication technology to make network intelligent is an important direction.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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