Journal of Computers Vol. 32 No. 3, 2021, pp. 86-98
doi:10.3966/199115992021063203007

Topology Control with Outage Probability Constraint in Wireless MIMO Ad Hoc Networks

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Received 18 August 2020; Revised 27 November 2020; Accepted 6 January 2021

Abstract. Wireless Ad Hoc network is composed of a collection of network nodes without fixed infrastructure and applied widely in different application areas. The multi-user multiple-input and multiple-output (MU-MIMO) transmissions with finite-rate feedback channel in wireless Ad Hoc networks may result in co-channel interference and inter-beamform interference. In the paper, we investigate the joint influence of the co-channel interference and inter-beamform interference on the transmission performance. Firstly we derive the outage probabilities in case of dedicated resource assignment and shared resource reuse. With the constraint that the outage probability shall not exceed some specified threshold, we further explore and perform a topology control on the network configurations, and the maximum values of the transmitting range and distribution density of transmitter nodes are obtained respectively. Finally we compare the topology configurations of single user MIMO (SU-MIMO) and MU-MIMO transmissions to evaluate the performance gain of MU-MIMO transmissions. The analytical and numeric results indicate the outage probability performance is influenced by the distribution density of transmitter nodes, especially for co-channel interference-limit system, and the configurations of network topology are restricted by the outage probability performance constraint.

Keywords: Ad Hoc networks, MU-MIMO, finite-rate feedback, outage probability, topology control

1 Introduction

Wireless Ad Hoc network is composed of a collection of nodes equipped with wireless transceiver. Without the help of infrastructure, the nodes communicate with each other directly or by multi-hop link [1]. Due to the agility network structure, wireless Ad Hoc networks are viewed as the ultimate frontier in wireless communication, and have attracted a lot of attentions in different application areas, such as military battlefield [2], post disaster reconstruction [3], emergency mission and vehicular communication [4].

Due to the lack of coordination of infrastructure or central node, the transmitter nodes in wireless Ad Hoc networks may transmit data packets simultaneously. In case that the nodes work on the same channel, it is inevitable that the transmissions interfere with each other. The co-channel interference that is named as inter-node interference in this paper impairs the transmission performance. Prior works [5-6] have evaluated the performance of wireless Ad Hoc networks with the present of co-channel inter-node interference, and some interference coordination schemes were proposed in [7-9].

In order to improve the aggregate throughput of wireless Ad Hoc network, MIMO has been exploited by many researchers [10-12]. Especially MU-MIMO attracts a lot of attentions due to its extremely high spectral efficiency [13-16]. In a MU-MIMO transmission, a transmitter node transmits data packets using orthogonal beamforms. The weights of beamforms are obtained according to the measurement information feedback from receiver nodes. In case that the feedback channel between receiver node and transmitter node is finite-rate, the weights may mismatch with the forward channel. The mismatch

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reduces the power of desired signal, and on the other hand destroys the orthogonality of beamforms. The non-orthogonal beamforms interfere with each other, and the interference that is named as intra-node interference in the paper affects the transmission performance additionally. Prior work [12] analyzed the outage probability performance of MIMO ad-hoc network with quantized beamforming and finite-rate feedback, but only SU-MIMO transmission was taken into account. In the similar work [14], Lee et al investigated the outage probability of MU-MIMO transmission in HetNet in the present of co-channel interference from coexistence ad hoc system and intra-node interference, while the influence of finite-rate channel on desired signal was not considered.

Motivated by the discussion above, in the paper, we investigate the joint influence of co-channel interference and finite-rate feedback channel on the outage probability performance and topology configurations. We assume a wireless Ad Hoc network employing MU-MIMO transmissions with finite-rate feedback channel. Considering different resource assignment, we first derive the outage probabilities in present of interference. In term of the outage probability constraint to satisfy the requirement of quality of service (QoS), then we perform a topology control on the topology configurations. The maximum values of transmitting range and distribution density of nodes are obtained respectively. Summarily our main contributions are given as follows.

— We explore the joint influence of co-channel interference and finite-rate feedback on the outage probability performance of MU-MIMO transmissions in wireless Ad Hoc networks.
— We derive the maximum values of topology configurations such that the outage probability satisfies QoS requirement.
— We evaluate the gain of network topology configurations for MU-MIMO transmissions, relative to SU-MIMO transmissions.

The remainder of the paper is organized as follows. In section 2, we describe our network model and MIMO model. In section 3, we evaluate the outage probability performance considering different resource assignment. A topology control on network configurations is performed to satisfy outage probability constraint in section 4. In section 5, the numeric results are shown. Finally we summarize our conclusions.

2 System Model

Considering the nodes in wireless Ad Hoc networks are arbitrarily placed in a region, we employ a stochastic geometry framework for modeling the random spatial distribution. Hence the randomly located nodes are assumed to be distributed according to a Spatial Poisson Point Process (SPPP) with intensity λ [17]. Each node is assumed to adopt the p-persistent slotted ALOHA [18]. In a slot, each node independently tries to send data packets to its receiver nodes with access probability p. We call a node who sends data packets as an active node, and denote the set of all active nodes as $\Phi\left(\lambda_p\right)=\left\{X_i\right\}$, where $\lambda_p = p\lambda$ and X_i is the position of active node i.

In a slot, each active node sends precoded data packets to $U\left(1 \le U \le N_t\right)$ selected receiver nodes simultaneously. The active node and receiver node are equipped with N_t antennas and single antenna respectively. We assume a MU-MIMO transmission occupies T_{tx} slots and operates in two phase: receiver nodes selection and data transmission, as shown in Fig. 1. In receiver nodes selection phase, the active node obtains measurement information feedback from K candidate nodes and selects $U\left(U \le K\right)$ best receiver nodes according to some rule. In second phase, the active node sends data packets to U selected receiver nodes simultaneously. Since we mainly explore the impact of finite-rate feedback, it is reasonable to assume the wireless channel is unvaried in T_{tx} slots.

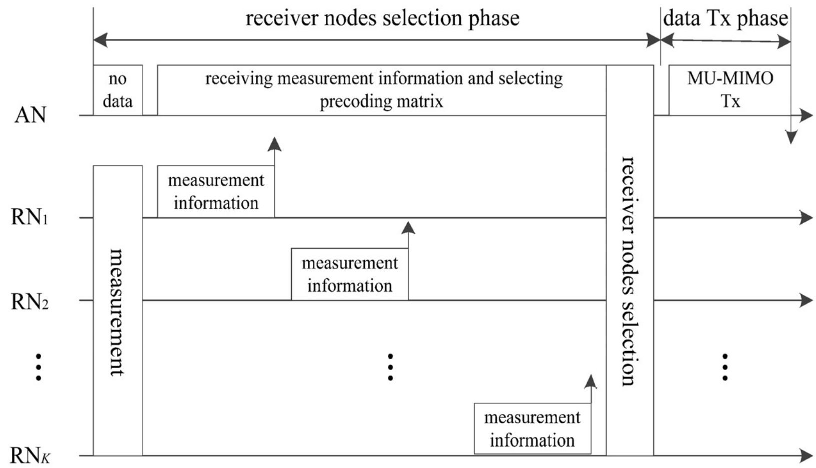

Fig. 1. Operation phases of MU-MIMO transmission

The wireless channel between an active node and U selected receiver nodes is assumed to be $\mathbf{H}=[\mathbf{h}_i]_{1\le i\le U}\in\mathbb{C}^{N_t\times U}$ with its entries distributed as $h_{i,j}\sim\mathcal{CN}(0,1)$. The precoding matrix $\mathbf{W}=[\mathbf{w}_i]_{1\le i\le U}\in\mathbb{C}^{N_t\times U}$ is selected from codebook in term of the feedback measurement information, where precoding vector $\mathbf{w}_i$ satisfies $\mathbf{w}_i^{\mathrm{H}}\mathbf{w}_i=1$ and $\mathbf{w}_i^{\mathrm{H}}\mathbf{w}_j=0(i\ne j)$. In case of finite-rate feedback channel, the receiver nodes quantize the measurement information by several bits and feedback them to active node, as shown in Fig. 2. For the convenience of describing the influence of finite-rate channel, we define the variable of quantization error as chordal distance between precoding vector $\mathbf{w}_i$ and the channel direction $\tilde{\mathbf{h}}_i$ [19], denoted as

$$z=\mathrm{d}^2\left(\mathbf{w}_i,\tilde{\mathbf{h}}_i\right)=1-\left|\tilde{\mathbf{h}}_i^{\mathrm{H}}\mathbf{w}_i\right|^2, \tag{1}$$

where superscript H represents conjugate transpose. $\tilde{\mathbf{h}}_i=\mathbf{h}_i/\|\mathbf{h}_i\|$ with $\|\cdot\|$ represents Euclidean norm. For full-rate feedback channel, $z=0$.

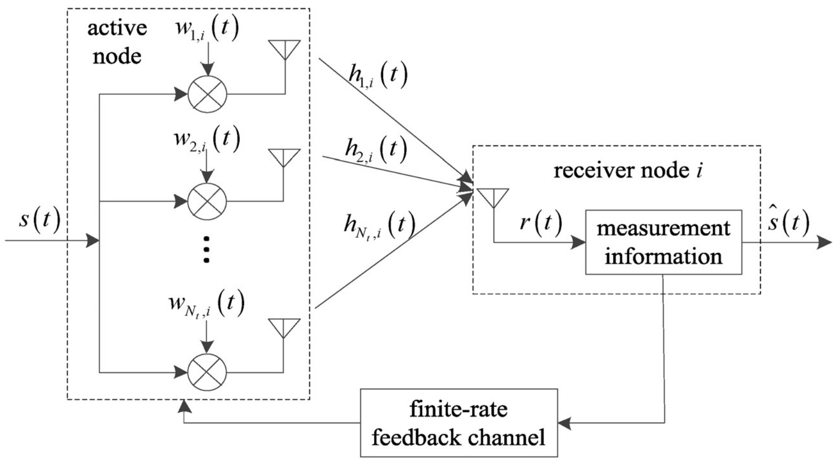

Fig. 2. MIMO system modeling with finite-rate feedback channel

Under the condition of quantization error, the conditional probability density function (PDF) of equivalent channel power $\left|\mathbf{h}_i^{\mathrm{H}}\mathbf{w}_i\right|^2$ for receiver node i is derived as

$$f(x|z)=\frac{x^{N_t-U}}{(N_t-U)!(1-z)^{N_t-U+1}}\exp\left(-\frac{x}{1-z}\right). \tag{2}$$

Note that if the number of receiver nodes U is equal to that of transmitting antennas N_t, the conditional PDF becomes an exponential distribution.

Moreover, the available frequency resource is assumed to divide into a collection of sub-channels. A MU-MIMO transmission may occur on a group of dedicated sub-channels, or share a group of sub-channels with other transmissions. Hence we consider two types of frequency resource assignment as follows to evaluate the influence of interference.

— Dedicated resource assignment. Due to the non-orthogonality of beamforms in MU-MIMO transmission when $U > 1$ and $z = 0$, a receiver node experiences intra-node interference signals from its active node but to different receiver nodes.

— Shared resource reuse. Multiple MU-MIMO transmissions interfere with each other in a slot. A receiver node suffers severe inter-node interference from other active nodes additionally.

3 Evaluation of Outage Probability Performance

Outage probability is a metric to evaluate the transmission performance, which is defined as the probability that received signal-interference-noise-ratio (SINR) does not exceed some specified threshold in the paper. For modeling and analysis, we tag a receiver node u_0 that is firstly indexed in U receiver nodes, and assume the tagged node to be located at origin. Further we give a definition and a proposition as follows to simplify the derivation of outage probability [20].

Definition 1. Given a Beta distributed random variable V with two positive shape parameters a and b, its cumulative distribution function (CDF) is a regularized incomplete beta function, denoted as

$$\begin{aligned} \mathcal{F}_v(a,b) &= \mathbb{P}(V \le v) \\ &= 1 - \sum_{i=1}^{a} \frac{\Gamma(b+i-1)}{\Gamma(b)\Gamma(i)} v^{i-1}(1-v)^b , \\ &= \sum_{i=1}^{b} \frac{\Gamma(a+i-1)}{\Gamma(a)\Gamma(i)} v^{a}(1-v)^{i-1} \end{aligned} \tag{3}$$

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

Proposition 1. For any $v \ge 0$, and non-negative integers n, m and r where $n \ge r$,

$$\sum_{k=0}^{n-r} \left(\frac{v}{1+v}\right)^k \binom{m+k-1}{k} = (1+v)^m \mathcal{F}_{\frac{1}{1+v}}(m, n-r+1) . \tag{4}$$

3.1 Outage Probability for Dedicated Resource Assignment

Assuming an active node t_0 serves the tagged receiver node u_0, and the distance between them is D, hence the received signal at tagged receiver node u_0 is denoted as

$$r = \sqrt{\frac{PD^{-\alpha}}{U}} \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_0 \mathbf{s}_0 + \sqrt{\frac{PD^{-\alpha}}{U}} \sum_{i=1}^{U-1} \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_i \mathbf{s}_i + n_0 , \tag{5}$$

where P is the total transmitting power of active node. α is path loss exponent and n_0 represents the additive white Gaussian noise (AWGN) with zero mean and variance of σ^2. Hence the received SINR at tagged node is expressed as

$$\gamma_0 = \frac{\frac{PD^{-\alpha}}{U} \left|\mathbf{h}_0^{\mathrm{H}} \mathbf{w}_0\right|^2}{\sigma^2 + \frac{PD^{-\alpha}}{U} \sum_{i=1}^{U-1} \left|\mathbf{h}_0^{\mathrm{H}} \mathbf{w}_i\right|^2} . \tag{6}$$

In case that the number of receiver nodes $U>1$ and the quantization error $z>0$, the beamforms for U receiver nodes interfere with each other, and the transmission system is an interference-limit system. Neglecting the AWGN for analysis simplicity, the outage probability p_{outage}, i.e. the probability that received SINR does not exceed a threshold γ_{exp}, is given as

$$\begin{aligned} p_{outage} &= \mathbb{P}\left[\gamma_0 \le \gamma_{exp}\right] \\ &= \mathbb{P}\left[S \le \gamma_{exp} I_{intra}\right] \\ &= \int_0^\infty \mathbb{P}\left(S \le \gamma_{exp} s\right) f_{I_{intra}}(s)\, ds \end{aligned} , \tag{7}$$

where $S=\left|\mathbf{h}_0^{\mathrm{H}}\mathbf{w}_0\right|^2$ and $I_{intra}=\sum_{i=1}^{U-1}\left|\mathbf{h}_0^{\mathrm{H}}\mathbf{w}_i\right|^2$ represent desired signal and intra-node interference signal respectively.

Considering the conditional PDF of desired signal S in equation (2), the probability of $\mathbb{P}\left(S \le \gamma_{exp} s\right)$ could be derived as

$$\begin{aligned} \mathbb{P}\left(S \le \gamma_{exp} s\right) &= \int_0^{\gamma_{exp} s} \frac{x^{N_t-U}}{(N_t-U)!(1-z)^{N_t-U+1}} \exp\left(-\frac{x}{1-z}\right) dx \\ &= 1 - \frac{1}{(N_t-U)!}\Gamma\left(N_t-U+1, \frac{\gamma_{exp} s}{1-z}\right) \end{aligned} , \tag{8}$$

where $\Gamma(p,x)=\int_x^\infty t^{p-1}e^{-t}\mathrm{d}t$ is complementary incomplete Gamma function with $p>0$.

Inserting the result into equation (7), the outage probability is further rewritten as

$$\begin{aligned} p_{outage} &= 1 - \int_0^\infty \sum_{k=0}^{N_t\text{-}U} \frac{(\omega s)^k}{k!} e^{-\omega s} f_{I_{intra}}(s)\, ds \\ &= 1 - \sum_{k=0}^{N_t\text{-}U} \frac{(-\omega)^k}{k!} \frac{d^k}{d\omega^k} \mathcal{L}_{I_{intra}}(\omega) \end{aligned} , \tag{9}$$

where $\omega=\frac{\gamma_{exp}}{1-z}$, $\mathcal{L}_{I_{intra}}(\cdot)$ represents the Laplace transform of random variable I_{intra}. In the derivation, the transforms of $\Gamma(p,x)=(p-1)!e^{-x}\sum_{k=0}^{p-1}\frac{x^k}{k!}$ and $\mathcal{L}\left[t^k f(t)\right]=(-1)^k F^{(k)}(s)$ are employed respectively, where q is a positive integer and $F^{(k)}(s)$ is the *k*-order differential of $F(s)$.

Note that the random variable I_{intra} obeys chi-square distribution with $2U-2$ degree of freedom, hence $\mathcal{L}_{I_{intra}}(\omega)$ and its *k*-order differential are respectively denoted as

$$\mathcal{L}_{I_{intra}}(\omega) = \frac{1}{(1+2\omega)^{U-1}}, \tag{10}$$

$$\frac{d^k}{d\omega^k}\mathcal{L}_{I_{intra}}(\omega) = \frac{(-2)^k}{(1+2\omega)^{U+k-1}} \prod_{l=0}^{k-1}(U+l-1). \tag{11}$$

Substituting the result in equation (11) into (9), the outage probability could be derived using a series of algebraic manipulation as

$$\begin{aligned} p_{outage} &= 1 - \sum_{k=0}^{N_t\text{-}U} \frac{(-\omega)^k}{k!} \frac{(-2)^k}{(1+2\omega)^{U+k-1}} \prod_{l=0}^{k-1} (U+l-1) \\ &= 1 - \frac{1}{(1+2\omega)^{U-1}} \sum_{k=0}^{N_t\text{-}U} \binom{U+k-2}{k} \left(\frac{2\omega}{1+2\omega}\right)^k \\ &= \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}} (N_t - U + 1, U - 1) \end{aligned} . \quad \textbf{(12)}$$

The result indicates that the outage probability is related to the system configurations such as the number of antennas instead of network topology.

In case of full-rate feedback channel or the number of receiver nodes $U=1$, the intra-node interference disappears and the transmission system is noise-limit system. According to the processing in (6)-(8), the outage probability is denoted as

$$\begin{aligned} p_{outage} &= \mathbb{P}\left[\frac{PD^{-\alpha}}{U} \left| \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_0 \right|^2 \le \sigma^2 \gamma_{exp} \right] \\ &= 1 - \frac{1}{(N_t - U)!} \Gamma\left(N_t - U + 1, \frac{\sigma^2 \gamma_{exp} U D^{\alpha}}{P(1-z)} \right) \end{aligned} . \quad \textbf{(13)}$$

Considering the power of AWGN is so small that the parameter $\frac{\sigma^2 \gamma_{exp} U D^{\alpha}}{P(1-z)}$ may be close to zero with some system configurations, we have $\Gamma\left(N_t - U + 1, \frac{\sigma^2 \gamma_{exp} U D^{\alpha}}{P(1-z)} \right) \approx (N_t - U)!$ and further the outage probability $p_{outage} \approx 0$.

3.2 Outage Probability for Shared Resource Reuse

In case of shared resource reuse, the tagged receiver node u_0 receives inter-node interference signal from other active nodes additionally. Hence the received signal at tagged receiver node u_0 is denoted as

$$r = \sqrt{\frac{PD^{-\alpha}}{U}} \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_0 \mathbf{s}_0 + \sqrt{\frac{PD^{-\alpha}}{U}} \sum_{i=1}^{U-1} \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_i \mathbf{s}_i + \sum_{X_j \in \Phi / t_0} \sqrt{P \left| X_j \right|^{-\alpha}} h_{0,X_j} s_{X_j} + n_0 , \quad \textbf{(14)}$$

where h_{0,X_j} is wireless channel between tagged receiver node u_0 and the active node $X_j \in \Phi / t_0$. s_{X_j} is the data symbols from the active node $X_j \in \Phi / t_0$ and $\mathbb{E}\left[\left\| s_{X_j} \right\|^2 \right] \le P$. Hence the received SINR at tagged node is expressed as

$$\gamma_0 = \frac{\frac{PD^{-\alpha}}{U} \left| \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_0 \right|^2}{\sigma^2 + \frac{PD^{-\alpha}}{U} \sum_{i=1}^{U-1} \left| \mathbf{h}_0^{\mathrm{H}} \mathbf{w}_i \right|^2 + \sum_{X_j \in \Phi / t_0} P \left| X_j \right|^{-\alpha} \left| h_{0,X_j} \right|^2} . \quad \textbf{(15)}$$

It is obvious that the transmission system is interference-limit system. In case that the number of receiver nodes $U > 1$ and the quantization error $z > 0$, the received SINR is affected by intra-node and inter-node interference. According to the processing in (7)-(9), the outage probability could be expressed as

$$\begin{aligned} p_{outage} &= 1-\frac{1}{\left(N_t-U\right)!}\int_0^\infty \Gamma\left(N_t-U+1,\omega s\right) f_{I_{intra}+I_{inter}}\left(s\right)ds \\ &= 1-\sum_{k=0}^{N_t\text{-}U}\frac{\left(-\omega\right)^k}{k!}\frac{d^k}{d\omega^k}\mathcal{L}_{I_{intra}}\left(\omega\right)\mathcal{L}_{I_{inter}}\left(\omega\right) \\ &= 1-\sum_{k=0}^{N_t\text{-}U}\frac{\left(-\omega\right)^k}{k!}\sum_{j=0}^{k}\binom{k}{j}\frac{d^j}{d\omega^j}\mathcal{L}_{I_{intra}}\left(\omega\right)\frac{d^{k\text{-}j}}{d\omega^{k\text{-}j}}\mathcal{L}_{I_{inter}}\left(\omega\right) \end{aligned}, \quad (16)$$

where $\omega=\frac{UD^\alpha\gamma_{exp}}{1-z}$, $I_{intra}=\frac{1}{UD^\alpha}\sum_{i=1}^{U-1}\left|\mathbf{h}_0^{\mathrm{H}}\mathbf{w}_i\right|^2$ and $I_{inter}=\sum_{X_j\in\Phi/t_0}\left|X_j\right|^{-\alpha}\left|h_{0,X_j}\right|^2$ represent intra-node and inter-node interference respectively. Note that the Leibniz rule is applied in the last step. The *k*-order differential of could be obtained by reference to results (10)-(11), denoted as

$$\frac{d^k}{d\omega^k}\mathcal{L}_{I_{intra}}\left(\omega\right)=\frac{\left(-2/\left(UD^\alpha\right)\right)^k}{\left(1+2\omega/\left(UD^\alpha\right)\right)^{U+k-1}}\prod_{l=0}^{k-1}\left(U+l-1\right). \quad (17)$$

In a slot, the active nodes is distributed according to SPPP modeling with intensity λ_p. Hence the inter-node interference could be modeled as a general Poisson shot noise process [21], and the Laplace transform of random variable I_{inter} is given as

$$\begin{aligned} \mathcal{L}_{I_{inter}}\left(\omega\right) &= \exp\left\{-2\pi\lambda_p\int_0^\infty\frac{x}{1+\left|x\right|^\alpha/\omega}\mathrm{d}x\right\} \\ &= \exp\left(-\lambda_p\mathcal{Q}\omega^\delta\right) \end{aligned}, \quad (18)$$

where $\delta=2/\alpha$ and $\mathcal{Q}=\pi\Gamma\left(\delta\right)\Gamma\left(1-\delta\right)$. Especially if the path loss exponent $\alpha=4$, we have $\mathcal{Q}=\pi^2$.

It is expected that the intensity λ_p is very small when a very strict outage probability constraint is required. Hence the k-order differential of $\mathcal{L}_{I_{inter}}\left(\omega\right)$ could be evaluated using first-order Taylor series around $\lambda_p\mathcal{Q}\omega^\delta=0$. For all $k\geq 1$, the *k*-order differential of $\mathcal{L}_{I_{inter}}\left(\omega\right)$ is given approximately as

$$\frac{d^k}{d\omega^k}\mathcal{L}_{I_{inter}}\left(\omega\right)\approx-\left(\lambda_p\mathcal{Q}\omega^{\delta-k}\prod_{m=0}^{k-1}\left(\delta-m\right)\right)e^{-\lambda_p\mathcal{Q}\omega^\delta}+\Theta\left(\lambda_p^2\mathcal{Q}^2\omega^{2\delta}\right). \quad (19)$$

Combining equation (16) with (17) and (19), the outage probability is expressed as

$$\begin{aligned} p_{outage}=1-\frac{e^{-\lambda_p\mathcal{Q}\omega^\delta}}{\left(1+2\omega D^{-\alpha}/U\right)^{U-1}}\Bigg\{&\sum_{k=0}^{N_t-U}\frac{1}{k!}\left(\frac{2\omega D^{-\alpha}}{U+2\omega D^{-\alpha}}\right)^k\prod_{l=0}^{k-1}\left(U+l-1\right) \\ &-\lambda_p\mathcal{Q}\omega^\delta\sum_{k=1}^{N_t-U}\frac{\left(-1\right)^k}{k!}\sum_{j=1}^{k}\binom{k}{j}\left(\frac{-2\omega D^{-\alpha}}{U+2\omega D^{-\alpha}}\right)^{k-j}\prod_{l=0}^{k-j-1}\left(U+l-1\right) \\ &\times\prod_{m=0}^{j-1}\left(\delta-m\right)+\Theta\left(\lambda_p^2\mathcal{Q}^2\omega^{2\delta}\right)\Bigg\} \end{aligned}. \quad (20)$$

With the proposition 1 and the transform $\prod_{l=0}^{k-1}\frac{\left(U+l-1\right)}{k!}=\binom{U+k-2}{k}$, we have $\sum_{k=0}^{N_t-U}\frac{1}{k!}\left(\frac{2\omega D^{-\alpha}}{U+2\omega D^{-\alpha}}\right)^k$ $\prod_{l=0}^{k-1}\left(U+l-1\right)=\left(1+\frac{2\omega}{UD^\alpha}\right)^{U-1}\mathcal{F}_{\frac{1}{1+2\omega D^{-\alpha}/U}}\left(U-1,N_t-U+1\right)$. Performing a first-order Taylor series expansion and discarding $\Theta\left(\lambda_p^2 \mathcal{Q}^2 \omega^{2\delta}\right)$, the result of outage probability in (20) is simplified as

$$\begin{aligned} p_{outage} =& \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right) \\ &+ \lambda_p \mathcal{Q} D^2 \left(\frac{U\gamma_{exp}}{1-z}\right)^{2/\alpha} \left(\mathcal{K} - \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right)\right), \end{aligned} \quad \textbf{(21)}$$

where $\mathcal{K} = 1 + \sum_{j=0}^{N_t-U-1} \binom{U+j-2}{j} \left(\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}\right)^j \sum_{l=1}^{N_t-j-1} \frac{1}{l!} \prod_{m=0}^{l-1} (m-\delta)$. The result is related to the distribution density of active nodes.

Especially in case of full-rate feedback channel or the number of receiver nodes $U = 1$, the reception at tagged receiver node u_0 just experiences inter-node interference. Putting $\mathcal{L}_{I_{inter}}(\omega)$ into equation (9) instead of $\mathcal{L}_{I_{intra}}(\omega)$, the outage probability is derived as

$$p_{outage} = \lambda_p D^2 \mathcal{Q} \mathcal{K}_0 \left(\frac{U\gamma_{exp}}{1-z}\right)^{2/\alpha}, \quad \textbf{(22)}$$

where $\mathcal{K}_0 = 1 + \sum_{l=1}^{N_t-U} \frac{1}{l!} \prod_{m=0}^{l-1} (m-\delta)$ satisfying $\Gamma^{-1}(1-\delta)(N_t - U + 1)^{-\delta} \le \mathcal{K}_0 \le (N_t - U + 1)^{-\delta}$.

4 Topology Control on Network Configurations

In case of dedicated resource assignment, the MU-MIMO transmissions are free of the influence of inter-node interference. The outage probability is irrelevant with the topology configurations such as the node density. Assuming the outage probability should not be greater than an outage threshold ε, there will be a maximum transmitting range of active node D_{max} satisfying $p_{outage}(D_{max}) = \varepsilon$. In term of the result in (13), we have $D_{max} \propto \left(\frac{P(1-z)(1-\varepsilon)}{U\sigma^2\gamma_0}\right)^{1/\alpha}$.

While in case of shared resource reuse, the MIMO transmissions suffer inter-node interference at less. The outage probability is closely related to the topology configurations of transmitting range and distribution density of active nodes. When the number of receiver nodes $U > 1$ and quantization error $z > 0$, we have the corollaries as follows.

Corollary 1. For a MU-MIMO transmission with outage probability constraint, there is a maximum transmitting range D_{max} of active node. If the distance between active node and receiver node satisfying $D \le D_{max}$, then $p_{outage}(D) \le \varepsilon$. The maximum transmitting range is given as

$$D_{max} = \left(\frac{1-z}{U\gamma_{exp}}\right)^{\frac{1}{\alpha}} \sqrt{\frac{\varepsilon - \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right)}{\lambda_p \mathcal{Q}\left(\mathcal{K} - \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right)\right)}}. \quad \textbf{(23)}$$

Corollary 2. There is a maximum distribution density of active nodes λ_p^{max} satisfying $p(\lambda_p) \le \varepsilon$ if the distribution density of active node $\lambda_p \le \lambda_p^{max}$. The maximum distribution density of active nodes is given as

$$\lambda_p^{max} = \left(\frac{1-z}{U\gamma_{exp}} \right)^{\frac{2}{\alpha}} \frac{\varepsilon - \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right)}{D^2 \mathcal{Q}\left(\mathcal{K} - \mathcal{F}_{\frac{2\gamma_{exp}}{1-z+2\gamma_{exp}}}\left(N_t - U + 1, U - 1\right) \right)} . \quad \textbf{(24)}$$

Especially in case of full-rate feedback channel or the number of receiver nodes $U = 1$, the maximum transmitting range of active nodes and the maximum distribution density of active nodes are simplified as

$$D_{max} = \left(\frac{1-z}{U\gamma_{exp}} \right)^{\frac{1}{\alpha}} \sqrt{\frac{\varepsilon}{\lambda_p \mathcal{Q} \mathcal{K}_0}} , \quad \textbf{(25)}$$

$$\lambda_p^{max} = \frac{\varepsilon}{D^2 \mathcal{A} \mathcal{K}_0} \left(\frac{1-z}{U\gamma_0} \right)^{2/\alpha} . \quad \textbf{(26)}$$

Using the bound value of $\mathcal{K}_0$, the ratios of maximum transmitting range and maximum distribution density for SU-MIMO and MU-MIMO are respectively denoted as

$$\frac{D_{max}^{SU}}{D_{max}^{MU}} = \left(\frac{N_t U}{N_t - U + 1} \right)^{\frac{1}{\alpha}} , \quad \textbf{(27)}$$

$$\frac{\lambda_p^{max,SU}}{\lambda_p^{max,MU}} = \left(\frac{N_t U}{N_t - U + 1} \right)^{\frac{2}{\alpha}} . \quad \textbf{(28)}$$

It is obvious that the configuration of network topology (i.e. the maximum transmitting range and the maximum distribution density of active nodes) in SU-MIMO transmissions could approach greater values with the same outage probability constraint. The reason is that the power of desired signal in SU-MIMO transmissions is more than that in MU-MIMO transmissions. Hence the SU-MIMO transmissions could tolerate stronger interference.

5 Numeric Results

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

Table 1. Simulation configurations

Parameter	Value
Total power of active node P (dBm)	23
Transmitting antenna N_t	4
Receiving antenna N_r	1
Receiver nodes number U	1,2,4
MU-MIMO scheme	ZF-based transmitter beamforming
Receiver nodes selection rule	Maximum SINR
Wireless channel	Rayleigh fading channel
Path loss exponent α	4
Distance between Tx and Rx D (m)	50~500
Distribution density of nodes λ (per km^2)	10~100
Outage probability threshold ε	0.01~0.1

Fig. 3 reflects the impact of quantization error on outage probability in the case of dedicated resource assignment. When the quantization error $z = 0$, the intra-node interference disappears because of the orthogonality of MU-MIMO transmissions and the outage probability performance is only related to AWGN. Hence the outage probability is approximately equal to zero, independent of the number of receiver nodes. In case of $U = 1$, the outage probability is same as that of $z = 0$, which is irrelevant with the variability of quantization error. While the number of receiver nodes $U > 1$, the intra-node interference caused by quantization error affects the outage probability performance, and the outage probability proportionally increases with the growth of quantization error. Because the increase of receiver nodes reduces the power of desired signal, the outage probability in case of $U = 4$ is greater than that of $U = 2$.

In case of shared resource reuse, as shown in Fig. 4, the outage probability performance is influenced by inter-node interference at least. Regardless of SU-MIMO or MU-MIMO transmission, the relativity of precoding vector and forward wireless channel decreases with the growth of quantization error. As a result, the power of desired signal decreases correspondingly, which results in outage probability increases. Same as the case of dedicated resource assignment, the increasing number of receiver nodes leads to the increase of outage probability. On the other hand, the increase of propagation distance between active node and receiver node also reduces the power of desired signal and received SINR, causing the outage probability increases.

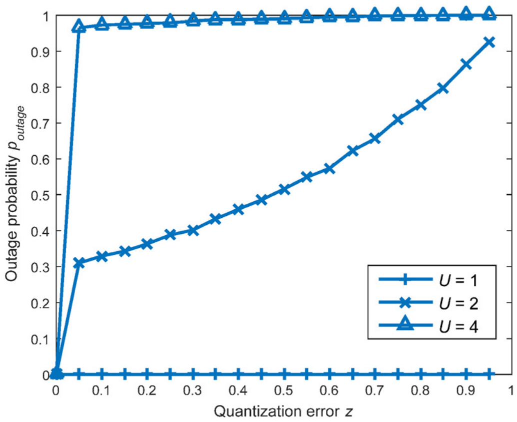

Fig. 3. Outage probability vs. quantization error (Dedicated frequency resource assignment)

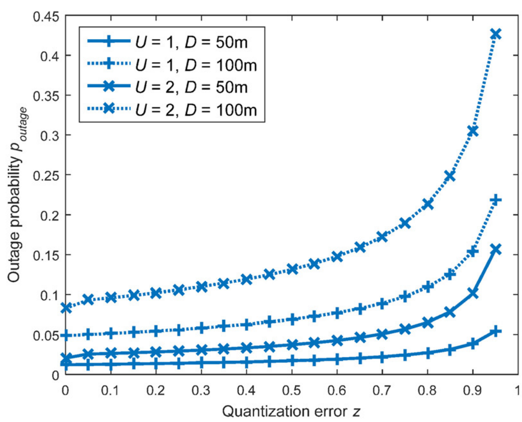

Fig. 4. Outage probability vs. quantization error (Shared frequency resource reuse)

Fig. 5 describes the relation between maximum transmitting range of active node and distribution density of active nodes. The growth of quantization error or receiver nodes number will cause weaker desired signal, and the growth of the distribution density of active nodes will generate stronger inter-node interference, which makes received SINR decreases but outage probability increases. If the outage probability threshold keeps constant, the maximum transmitting range correspondingly decreases. Especially when the quantization error $z = 0$, the maximum transmitting range of SU-MIMO transmissions is approximately twice as much as that of MU-MIMO transmissions ($U = 4$), which is consistent with the analysis above.

Fig. 6 gives the relation between maximum distribution density of active nodes and propagation distance between active node and receiver node. The growth of propagation distance or receiver node number leads to the desired signal power decreases but the outage probability increases. With constant outage probability constraint, the maximum contention density decreases. Consistent with the analysis above, the maximum contention density of SU-MIMO transmissions is approximately 1.6 times or four times as much as that of the transmissions of $U = 2$ or $U = 4$.

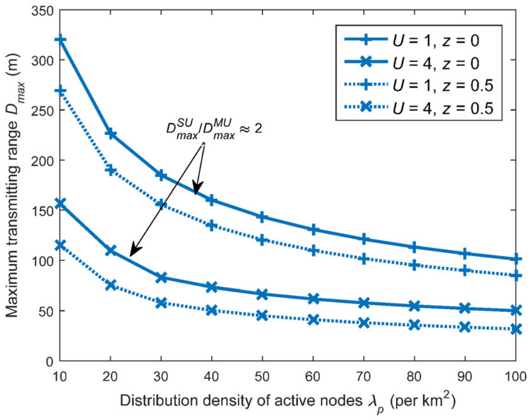

Fig. 5. Maximum transmitting range vs. distribution density of active nodes

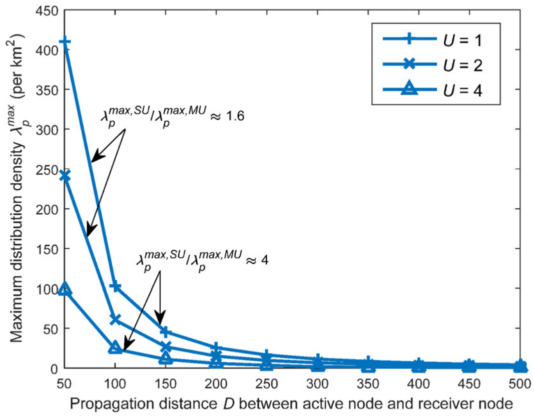

Fig. 6. Maximum distribution density vs. propagation distance between active node and receiver node ($z = 0$)

Fig. 7 and Fig. 8 show the impact of outage probability threshold on maximum transmitting range and maximum distribution density respectively. With the relaxation of outage probability constraint, a larger value of outage probability is acceptable. This means that the decoding at receiver node could tolerate weaker desired signal or stronger interference signal. Hence the maximum transmitting range that could cause weaker desired signal and the maximum distribution density that could cause stronger inter-node interference signal increase correspondingly.

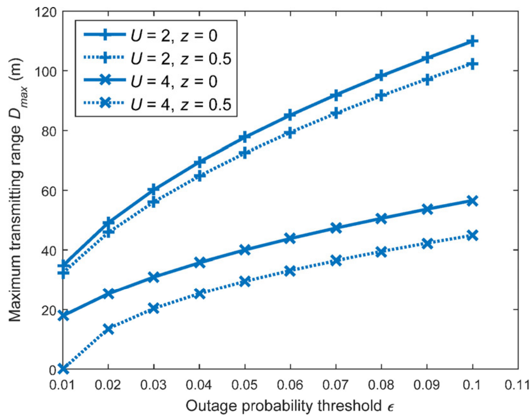

Fig. 7. Maximum transmitting range vs. outage probability threshold

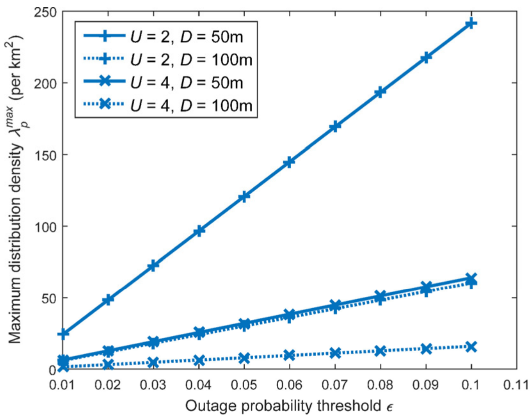

Fig. 8. Maximum distribution density of active nodes vs. outage probability threshold

6 Conclusions

This paper evaluates the joint influence of co-channel interference and finite-rate channel on the outage probability performance of an MU-MIMO transmission in wireless Ad Hoc networks. The outage probabilities are derived in present of intra-node and inter-node interference considering different resource assignment. With the outage probability constraint to satisfy QoS requirement, a topology control on network configurations, such as transmitting range and distribution density of active nodes, is performed and the maximum values of configurations are obtained. The analytical and numeric results indicate the outage probability is influenced by the distribution density of active nodes in inter-node interference-limit system, and the configurations of network topology are limited by the outage probability constraint.

We admit there are some limitations in the paper. For instance, the mobility of nodes is not taken into account. Hence as a future work, we will explore the influence of node mobility on the transmission performance and network connectivity. In addition, based on the derived results, the optimization of transmission performance by interference management or resource assignment shall be developed in the future. At the same time, we believe that the application of integrated cognition-control-communication technology to make network intelligent is an important direction.

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