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Abstract

This paper presents a new approach for terminal presence detection in the family of training-based algorithms for random access called network diversity multiple access (NDMA). In NDMA, system-induced retransmissions are used to resolve the conflicts between colliding terminals. The key aspect in NDMA is to use signal processing tools to identify the size of the collision, as well as the identity of the contending terminals. This information is used to calculate the number of required retransmissions. These retransmissions are kept in memory, thereby creating a virtual MIMO (multiple input multiple-output) system that can be used to resolve the collision via source separation or mutiuser detection. These detection and source separation processes are based on a set of orthogonal training sequences, each sequence uniquely assigned to one terminal in the network. This paper proposes a new approach for NDMA using non-orthogonal training sequences. The number of available sequences is increased and the bandwidth used for training is therefore considerably reduced. This comes at the expense of multiple access interference between contending terminals. Additionally, in conventional NDMA the estimation of the collision multiplicity is conventionally achieved in the first time-slot of the collision resolution period. This paper extends the detector to include all the received copies of the original transmissions (the initial transmission and also subsequent retransmissions). This means that after each retransmission received by the base station, the estimation of the collision multiplicity and contending terminals identification must be updated. The analysis here presented includes the effects of multiple access interference caused by non orthogonal training sequences and the effect of sequential collision multiplicity estimation. Results suggest a decrease of performance with respect to the orthogonal case scenario, but a more flexible training sequence allocation that becomes relevant for large numbers of terminals.

Performance Analysis of Network Diversity Multiple Access with Sequential Terminal Detection and Non-Orthogonal Training Sequences

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***Abstract*—This paper presents a new approach for terminal presence detection in the family of algorithms called network diversity multiple access (NDMA). In NDMA, system-induced retransmissions are used to resolve the conflicts between colliding terminals. The key initial aspect in NDMA is to use signal processing tools to identify the size of the collision, as well as the identity of the contending terminals. This information is used to calculate the number of required retransmissions. These retransmissions are stored in memory, thereby creating a virtual MIMO (multiple input multiple-output) system that can be used to resolve the collision via source separation or multi-user detection. These detection and source separation processes are based on a set of orthogonal training sequences, each sequence uniquely assigned to one terminal in the network. This paper proposes a new approach for presence detection in NDMA using non-orthogonal sequences. The number of available sequences is increased and the bandwidth used for training is therefore considerably reduced. This comes at the expense of multiple access interference (MAI) between contending terminals. Additionally, in NDMA the estimation of the collision multiplicity is conventionally achieved exclusively in the first time-slot of the collision resolution period. This paper extends the detector to include all the received copies of the original transmissions (the initial transmission and also subsequent retransmissions). This means that after each retransmission is received by the access point, the estimation of the collision multiplicity and contending terminals identification must be updated. The analysis here presented includes the effects of MAI caused by non orthogonal training sequences and the effect of sequential collision multiplicity estimation. Results suggest a considerably decrease of detection performance with respect to the orthogonal case scenario, but a more flexible training sequence allocation that becomes relevant for large numbers of terminals.**

I. Introduction

Three main requirements are foreseen in future industrial wireless networks: high criticality, ultra-low latency, and high scalability for billions of distributed embedded devices foreseen in smart city applications. Typical allocation schemes are not suitable in these large set-ups, mainly due to scarce spectrum and signalling resources. A new generation of multiple access and resource allocation is expected for 5G [1].

Random access protocols are regaining attention in academic circles, mainly because of their low signalling requirements and low latency features at relatively low traffic loads. Their main disadvantage is the degrading effect of collisions when traffic loads are moderately high. However, the last two decades have witnessed a considerable improvement of random access using signal processing. Multi-packet reception (MPR) is the ability to decode simultaneously more than one transmission in random access [2]-[4].

One particularly attractive solution for MPR in random access was presented in [5] using retransmissions. The algorithm was called network diversity multiple access (NDMA). In NDMA, the access point (AP) uses signal processing to detect the presence of active terminals and thus estimate the collision multiplicity. Based on this information, the AP requests a number of retransmissions from the contending terminals. These signals are stored in memory in an attempt to create a virtual multiple-input multiple-output (MIMO) system that can be used to recover the original signals. In comparison with conventional MPR algorithms, NDMA can deal, in theory, with collisions of any size, as the system can request as many retransmissions as necessary to resolve collisions of variable size. NDMA can also be combined with conventional multiple antenna MPR capabilities or successive interference cancellation (SIC) (see [6]), thus further reducing the number of retransmissions required to resolve collisions.

Training-based versions of NDMA in non-dispersive and dispersive channels have been proposed in [5] and [7], respectively. Blind versions have also been proposed in [8] using rotational invariance techniques, and in [9] using independent component analysis (ICA). The cooperative version of NDMA has been investigated in [10]. Optimization of asymmetrical NDMA protocols with carrier-sensing has been addressed in [11]. Stability of asymmetrical NDMA with perfect detection/reception has been proposed in [12]. Stability of NDMA protocols with imperfect collision multiplicity estimation in symmetrical settings was studied in [13] using a Markov model. NDMA incorporating MPR and successive interference cancellation was proposed in [6]. Performance of NDMA with Automatic Repeat reQuest (ARQ) is addressed in [14].

Conventionally, NDMA uses orthogonal training sequences to achieve terminal presence detection, channel/collision multiplicity estimation, and source separation. However, in future systems with hundreds or thousands of objects with embedded distributed communication capabilities, the use of orthogonal training sequences can become prohibitely large in terms of spectrum usage. To alleviate this issue, this paper proposes the use of non-orthogonal training sequences for

NDMA, which allows for the increase of training sequences with minimum spectrum expenditure. This is achieved at the expense of the multiple access interference (MAI) created by the non-orthogonality condition of the sequences allocated to active terminals. All protocol expressions and the receiver operational characteristic (ROC) of the terminal presence detector are modified here to account for non-orthogonality feature. Conventionally, the NDMA protocol uses the training sequences for terminal presence detection and collision multiplicity estimation exclusively in the first time slot of any collision resolution period. It has been pointed out before in the literature of NDMA [5][7], that the identity of the contending terminals, and the collision multiplicity can also be updated after the reception of each retransmissions, thus contributing to an improvement of the estimation process. In our previous work in [15], sequential detection showed high gains particularly at high traffic loads. This previous work did not provide a theoretical framework for exact closed form expressions of the ROC of a sequential terminal detection process in NDMA. This paper aims to partially fill this gap, and provide expressions that allow us to optimize the exact detection performance of the protocol with sequential detection mechanisms and non-orthogonal training sequence design.

This paper is organized as follows. Section II describes the assumptions of the paper and system model. Section III presents the design of the terminal detector. Section IV presents the derivation of performance metrics and the results of simulation. Finally, Section V draws the conclusions.

Notation: Bold lower case letters (e.g., $\mathbf{x}$) denote vector variables, bold upper case letters (e.g.,$\mathbf{A}$) denote matrices, $(\cdot)^T$ is the vector transpose operator, $E[\cdot]$ is the statistical average operator, $(\cdot)^*$ is the complex conjugate operator, $\bar{(\cdot)} = 1-(\cdot)$ is the complement to one operator, e.g. $\bar{a} = 1-a$, $|\cdot|$ is the set cardinality operator when applied to a set variable or the absolute value operator when applied to a scalar quantity, and $(\cdot)^H$ is the Hermitian vector transpose operator. $\hat{(x)}$ indicates the estimator of the random variable x, and $\check{(x)}$ the value of x conditional on channel conditions. The term $\nu_{r,\lambda}(y)$ denotes the probability density function (PDF) of a central chi-square distribution of order r with parameter λ. $f_x(x)$ and $\bar{F}_x(x)$ denote respectively, the PDF and complementary cumulative distribution function (CCDF) of any random variable x. $\mathcal{F}\{\cdot\}$ is the Fourier transform operator for PDFs. $\mathbf{0}_Q$ and $\mathbf{I}_Q$ denote, respectively the vector of Q zeros and the identify matrix of order Q. $i = \sqrt{-1}$ is the complex number and ω is the frequency domain variable for PDFs.

II. System model

Consider the slotted random access network depicted in Fig. 1 with a set of J buffered one-antenna terminals and one central node or access point (AP) with one receiver antenna. The channel between terminal j and the AP in time-slot n of any resolution period is denoted by $h_j(n)$. All channel envelopes are assumed to be non-dispersive with Rayleigh statistics: $h_j \sim \mathcal{CN}(0,\gamma)$.

NDMA makes use of adaptive retransmissions to resolve conflicts. This can be observed in Fig. 1 where four resolution periods with a random number of time slots (due to adaptive retransmissions) are used to deal with different collisions. Every time the AP detects the presence of a collision, it proceeds to estimate the number of retransmissions required to resolve a collision. Retransmissions are collected over a random number of time-slots as decided by the AP. Multi-user decoding is then used to recover the contending signals. Details of each process of the NDMA protocol (detection, estimation, retransmission request, and signal decoding) are described in following subsections. The period of time used to resolve a collision is called contention resolution period or *epoch-slot* [5] and its length will be denoted by the random variable l. The set of terminal that collide at the beginning of any resolution period will be denoted by $\mathcal{T}$, and the set of terminals detected at the AP using the sequential detector proposed in this paper in time slot n of any epoch will be denoted by $\hat{\mathcal{T}}(n)$. The probability of transmission at the beginning of an epoch slot will be denoted by p.

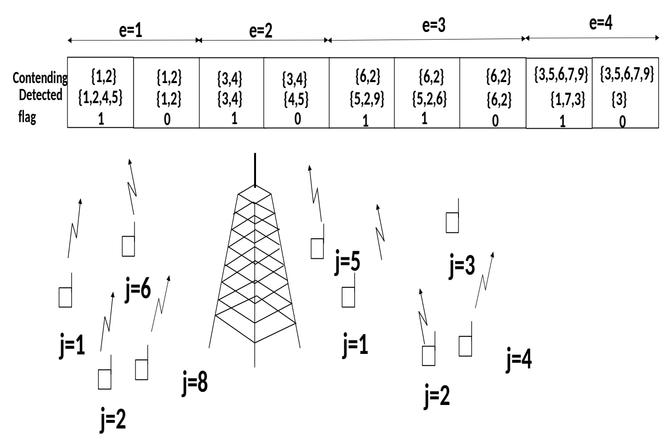

Fig. 1. Network-diversity multiple access with sequential detection.

Fig. 1 shows four examples of collision resolution in NDMA at the AP and the effects of sequential terminal detection. In the first epoch slot ($e=1$), two terminals collide at the first time slot $\mathcal{T} = \{1,2\}$. The detector of the AP has detected $\hat{\mathcal{T}}(1) = \{1,2,4,5\}$. Since the number of detected terminals suggests more retransmissions are necessary, the feedback flag is set to '1' to indicate to the involved terminals to retransmit immediately in the next time slot. With the new retransmission, the AP process to update the set of terminals detected as active. This time, the detected terminals coincide with the set of colliding terminals. The two signals coming from active terminals can be resolved in two time slots. Therefore, the AP sets the flag to '0', which signals the end of the resolution period. Since the identity of the contending terminals and the number of required retransmissions have been correctly estimated, the resolution process has been successful for the 2 signals. The second epoch $e=2$ shows the case of underestimation of the identity of the contending terminals but correct number of retransmisions, while epoch $e=3$ shows an overestimation of the size of the collision, but in the end a correct estimation of the terminals involved in the collision. Finally epoch $e=4$ shows the example where the detection mechanism incorrectly estimates both the identity of the terminals and the number of retransmissions, yielding the loss of all the contending signals.

A. Signal model

Each terminal is pre-assigned with an non-orthogonal code consisting of Q_t symbols: $\mathbf{w}_j = [w_j(0), w_j(1), \ldots, w_j(Q_t - 1)]^T$. This code is attached as header of each packet transmission of terminal j, and is employed for purposes of presence detection (collision multiplicity estimation) and channel estimation. The non-orthogonality condition of the set of codes is given by: $\mathbf{w}_j^H \mathbf{w}_k = \begin{cases} \delta_j, & k = j \\ \delta_{j,k}, & k \neq j \end{cases}$. The conventional NDMA protocol employs Hadamard orthogonal codes whose length increases linearly with the number of sequences: for 16 terminals, the code is of length 16. Note the huge waste of potential sequences from 2^{16} down to only 16. Non-orthogonal sequences aim to reduce this inefficiency and allow more terminals to be included in resource allocation. The received signal from all the headers of the set of contending users $\mathcal{T}$ in time-slot n of an epoch-slot can be written as:

$$\mathbf{y}^{(h)}(n) = \sum_{j \in \mathcal{T}} h_j(n) \mathbf{w}_j + \mathbf{v}^{(h)}(n), \tag{1}$$

where $\mathbf{v}^{(h)}(n) = [v_0^{(h)}(n), \ldots, v_{Q_t-1}^{(h)}(n)]^T$ is the zero-mean and white complex Gaussian noise vector in the header: $\mathbf{v}^{(h)} \sim \mathcal{CN}(\mathbf{0}_{Q_t}, \sigma_v^2 \mathbf{I}_{Q_t})$. The AP uses a matched-filter operation ($\mathbf{w}_j^T \mathbf{y}^{(h)}$) to detect the presence of terminal j across each antenna. The results from all the antennas are then combined as follows:

$$z_{j,n} = \sum_{\tilde{n}=1}^{n} |\mathbf{w}_j^T \mathbf{y}^{(h)}(\tilde{n})|^2 = \sum_{\tilde{n}=1}^{n} \alpha_{j,n} = z_{j,n-1} + \alpha_{j,n}. \tag{2}$$

The total detection indicator $z_{j,n}$ for terminal j in time-slot n is compared to a detection threshold β_n to decide whether terminal j is active or not. If $z_{j,n} < \beta_n$ then the terminal is detected as inactive: $j \notin \widehat{\mathcal{T}}(n)$. Otherwise, if $z_{j,n} > \beta_n$ then the terminal is detected as active ($j \in \widehat{\mathcal{T}}(n)$). Since this detection process is prone to errors due to channel fading and noise, two cases of active detection can be identified: 1) terminal j can be correctly detected as active in time slot n with probability $P_{D,n}$ provided the terminal has transmitted a packet, and 2) terminal j is incorrectly detected as active in time slot n with probability $P_{F,n}$ (probability of false alarm) provided the terminal did not transmit a packet. By detecting each one of the contending terminals, the AP also has an estimation $\hat{K}_n = |\widehat{\mathcal{T}}(n)|$ of the real collision multiplicity $K = |\mathcal{T}|$.

Unlike the conventional NDMA protocol, where the AP estimates the collision multiplicity only during the first time slot of an epoch, in this paper the AP is assumed to refine this estimation after the collection of every retransmission within a collision resolution period. Therefore, the estimated number of retransmissions required to resolve the collision is also updated. Since the AP has one receive antenna, the number of transmissions (including the initial transmission plus retransmissions) required in the non-blind version of NDMA is given by $\widehat{K}_n$. This means that the number of diversity sources must be greater than or equal to the estimated collision multiplicity. To request a retransmission for diversity purposes, the AP simply indicates with a feedback flag at the end of each time-slot to all the contending users that retransmission is required in the next time slot. The feedback flag is kept active until all necessary retransmissions have been collected. This feedback channel is assumed to be ideal.

The signal received by the AP in time slot n can be written as follows:

$$\mathbf{y}(n) = \sum_{j \in \mathcal{T}} h_j(n) \mathbf{s}_j + \mathbf{v}(n), \tag{3}$$

where $\mathbf{s}_j = [s_j(0), s_j(2), \ldots, s_j(Q-1)]^T$ is the vector of Q symbols transmitted by terminal j, and $\mathbf{v}(n) = [v_0(n), \ldots, v_{Q-1}(n)]^T$ is the zero-mean and white complex Gaussian noise vector: $\mathbf{v} \sim \mathcal{CN}(0, \sigma_v^2 \mathbf{I})$. All the collected (re)transmissions are stored in memory to create a MIMO system that can be expressed as follows [5] [12]:

$$\mathbf{Y}_{\widehat{K} \times Q} = \mathbf{A}_{\widehat{K} \times Q} \mathbf{S}_{K \times Q} + \mathbf{V}_{\widehat{K} \times Q}, \tag{4}$$

where $\mathbf{Y}$ is the collection of all received signal from the $\widehat{K}$ time-slots of the epoch, $\mathbf{A}$ is the mixing or MIMO channel matrix, $\mathbf{S}$ is the array of stacked packets from all the contending users, each one with Q symbols, and finally $\mathbf{V}$ is the collected Gaussian noise vector. The mixing matrix $\mathbf{A}$ can be estimated by using the outcome of the matched filter operation from each antenna. The estimate $\hat{\mathbf{A}}$ can be used to recover the contending packets using a zero forcing equalizer: $\hat{\mathbf{S}} = (\hat{\mathbf{A}}^H \hat{\mathbf{A}})^{-1} \hat{\mathbf{A}}^H \mathbf{Y}$, or a minimum mean square error (MMSE) receiver: $\hat{\mathbf{S}} = (\hat{\mathbf{A}}^H \hat{\mathbf{A}} + \sigma_v^2 \mathbf{I})^{-1} \hat{\mathbf{A}}^H \mathbf{Y}$, where the term $\hat{\mathbf{S}}$ indicates the soft estimate of the contending packets. This signal is then passed through hard symbol detection to recover the original packets $\mathbf{S}$ [5].

To facilitate NDMA MAC layer design, packet reception performance is usually approximated by the outcome of the collision multiplicity detector [5]. If all the contending users are correctly detected as active and none of the non-contending uses are incorrectly detected as active (false alarm) then all the packets are considered as correctly received by the AP. Otherwise, all packets are assumed to be lost in the collision resolution process. These protocol steps are repeated for subsequent epoch-slots.

III. Detector performance model

This section deals the modelling of the terminal presence detector indicator in (2). The probability of false alarm of a terminal that did not transmit a signal while still being detected as active in time slot n can be defined formally as follows:

$$P_{F,n} = \Pr\{z_j(n) > \beta_n | j \notin \mathcal{T}\}, \tag{5}$$

which is the probability that $z_j(n)$ is above the detection threshold β_n, conditional on terminal j not being one of the contending terminals. Similarly, the probability of detection $P_{D,n}$ can be defined as the probability that $z_j(n)$ is above the detection threshold β_n, conditional on terminal j being one of the contending terminals in time slot n:

$$P_{D,n} = \Pr\{z_j(n) > \beta_n | j \in \mathcal{T}\}, \tag{6}$$

Let us now substitute in the definition of $\alpha_{j,n}$ in (2) the non-orthogonality condition of the training sequences and the expression for the received signal at the from (1):

$$\alpha_{j,n} = \left| \kappa_{j,n} + \sum_{q=1}^{Q_t} v_q^{(h)}(n) \right|^2, \tag{7}$$

where

$$\kappa_{j,n} = \begin{cases} \delta_j h_j(n) + \sum_{k\in\mathcal{T};k\neq j} \delta_{j,k} h_k(n), & j \in \mathcal{T} \\ \sum_{k\in\mathcal{T}} \delta_{j,k} h_k(n), & j \notin \mathcal{T} \end{cases} \tag{8}$$

The expression in (7) conditional on $\kappa_{j,n}$ can be identified as a non-central Chi-square random variable with non-centrality parameter given by $\kappa_{j,n}$. The conditional PDF of $\alpha_{j,n}$ can be therefore written as follows:

$$\check{f}_{\alpha_{j,n}}(y) = \sum_{r=0}^{\infty} C_{r,j}(n) \nu_{r,\lambda}(y) \tag{9}$$

where $C_{r,j}(n) = \frac{\kappa_{j,n}^r}{r!} e^{-\kappa_{j,n}}$ and $\lambda = Q_t \sigma_v^2$. Consider the binary random variable $t_{j,n}$ that indicates whether terminal j was detected as active ($t_{j,n} = 1$) or not ($t_{j,n} = 0$) in the nth time slot of a resolution period. The PDF of the combined detection signal $z_{j,n}$ from different time slots conditional on the detection outcomes of the previous time slots (denoted as $\mathbf{t}_{j,n} = [t_{j,1}, \dots t_{j,n}]$) can be written as a piecewise function model for the different intervals defined by the detection thresholds β_n, each one expanded as an infinite series of central chi-square distributions as follows:

$$\check{f}_{z_{j,n}}(y) = \check{f}^{(\tilde{n})}_{z_{j,n}|\mathbf{t}_{j,n}}(y) = \sum_{r=0}^{\infty} \tilde{C}^{(\tilde{n})}_{r,j,n} \nu_{r,\lambda}(y), \quad \beta_{\tilde{n}} \leq y \leq \beta_{\tilde{n}+1}.$$

Note that $\check{f}^{(\tilde{n})}_{z_{j,n}|\mathbf{t}_{j,n}}(y) = 0$, $\tilde{n} < n^*$, where n^* indicates the index of the vector $\mathbf{t}_{j,n}$ with the last element with value $t_{j,\tilde{n}} = 1$. This simply means that once the indicator $z_{j,n}$ is detected as higher than the detection threshold β_n, the PDF for values lower than this threshold does not exist. The conditional PDF of the combined signal detection indicator $z_{j,n}$ in time slot n can be obtained as the convolution integral of the PDF of the indicator variable in the previous time slot $n-1$ and the PDF of the signal in the current time slot $\alpha_{j,n}$. This can be written as follows:

$$\check{f}^{(\tilde{n})}_{z_{j,n}|\mathbf{t}_{j,n}}(y) = \check{f}^{(\tilde{n}-1)}_{z_{j,n}|\mathbf{t}_{j,n}}(\beta_{\tilde{n}}) + \int_{\beta_{\tilde{n}}}^{y} \hat{f}^{(\tilde{n}-1)}_{z_{j,n-1}|\mathbf{t}_{j,n}}(y) f_{\alpha_{j,n}}(y-x)dx$$

From the explicit PDF expression we can obtain the conditional probability of detection and the probability of false alarm, respectively, as the CCDF valued at β_n:

$$\check{P}_{D,j,n} = \hat{\bar{F}}^{(\tilde{n})}_{z_{j,n}|\mathbf{t}_{j,n}}(\beta_{\tilde{n}}) \qquad j \in \mathcal{T}$$

$$\check{P}_{F,j,n} = \hat{\bar{F}}^{(\tilde{n})}_{z_{j,n}|\mathbf{t}_{j,n}}(\beta_{\tilde{n}}) \qquad j \notin \mathcal{T}$$

The conditional probability of correct detection of all terminals in a specific realization of epoch length l and collision set $\mathcal{T}$:

$$\check{\Pr}\{\hat{\mathcal{T}}(l) = \mathcal{T}|l\} = \prod_{k\in\mathcal{T}} \check{P}_{D,k,l} \prod_{\tilde{k}\notin\mathcal{T}} \check{\bar{P}}_{F,\tilde{k},l} \tag{10}$$

The probability mass function (PMF) of the length of a resolution period can be expressed as the average over all realizations of set of contending terminals as follows:

$$\Pr\{l = \tilde{l}\} = \sum_{\mathcal{T}|K>0} \Pr\{\mathcal{T}\}\Pr\{l = \tilde{l}|\mathcal{T}\},$$

where $\Pr\{\mathcal{T}\} = \prod_{k\in\mathcal{T}} p_k \prod_{\tilde{k}\notin\mathcal{T}} \bar{p}_j$ is the probability of occurrence of the collision set $\mathcal{T}$, and $\Pr\{l = \tilde{l}|\mathcal{T}\}$ is the PMF of the length of an epoch conditional on a specific realization collision set $\mathcal{T}$. This PMF term conditional on specific channel realizations can be written as follows:

$$\check{\Pr}\{l = \tilde{l}|\mathcal{T}\} = \begin{cases} \prod_{n=1}^{\tilde{l}-1} \sum_{\mathbf{t}_n|\frac{\hat{K}_n}{n}\leq 1} \check{\Pr}\{\mathbf{t}_n|\mathbf{t}_{n-1}\}, & \\ \times \sum_{\mathbf{t}_n|\hat{K}_n/n\geq 1} \check{\Pr}\{\mathbf{t}_n|\mathbf{t}_{n-1}\} & \tilde{l} < J \\ \prod_{n=1}^{J-1} \sum_{\mathbf{t}_n|\frac{\hat{K}_n}{n}\leq 1} \check{\Pr}\{\mathbf{t}_n|\mathbf{t}_{n-1}\}, & \tilde{l} = J \end{cases} \tag{11}$$

where

$$\check{\Pr}\{\mathbf{t}_n|\mathbf{t}_{n-1}\} = \prod_{k\in\hat{\mathcal{T}}(n);k\notin\mathcal{T}} \check{P}_{F,k,n} \prod_{k\in\hat{\mathcal{T}}(n);k\in\mathcal{T}} \check{P}_{D,k,n}$$
$$\prod_{k\notin\hat{\mathcal{T}};k\notin\mathcal{T}} \check{\bar{P}}_{F,k,n} \prod_{k\notin\hat{\mathcal{T}}(n);k\in\mathcal{T}} \check{\bar{P}}_{D,k,n} \tag{12}$$

The joint probability of correct detection of all the active terminals in exactly the number of time slots that is equal to the size of the collision set is given by:

$$\check{\Pr}\{\hat{T}(l) = \mathcal{T}, l = K|\mathcal{T}\} = \prod_{n=1}^{K-1} \sum_{\mathbf{t}_n|\frac{\hat{K}_n}{n}\leq 1} \check{\Pr}\{\mathbf{t}_n|\mathbf{t}_{n-1}\}$$
$$\times \prod_{k\in\mathcal{T}} \check{P}_{D,k,K} \prod_{\tilde{k}\notin\mathcal{T}} \check{\bar{P}}_{F,\tilde{k},K} \tag{13}$$

The unconditional PMF of the epoch length and the correct terminal detection probability can be obtained by averaging (numerically) the previous expressions over the channel space of the terminals. Optionally, this averaging operation can be conducted in the frequency domain, where the product of different probability terms can be found to be expressed in the frequency domain (ω) as follows:

$$\mathcal{F}\left\{\prod_u P_u\right\} = \sum_{r=0}^{\infty} \left(\sum_u \kappa_u\right)^r (i\omega)^{-r}(1 - i\omega\lambda)^{-r}.$$

The averaging operation is obtained over the channel states that are contained in the terms κ_u, which are the non-centrality parameters of the infinite series expansion of all the set of probability expressions. The inverse Fourier transform yields the desired unconditional probability expression.

IV. Performance metrics and results

The detector throughput of NDMA is defined as the ratio of epoch lengths with all terminals correctly detected to the average length of an epoch. The detector throughput can be used as a boundary of the full performance of NDMA. This can be expressed as follows:

$$T_d = \frac{\sum_{\mathcal{T},l} |\mathcal{T}| \Pr\{\hat{T}(l) = \mathcal{T}, l = K|\mathcal{T}\}\Pr\{\mathcal{T}\}}{E[l] = \sum_{\tilde{l}=1}^{J} \tilde{l}\Pr\{l = \tilde{l}\}}. \tag{14}$$

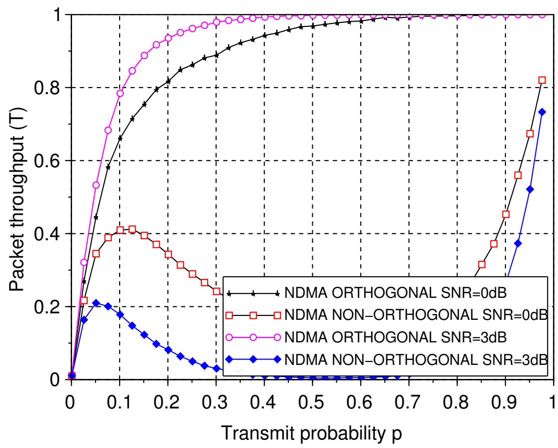

Fig. 2. Throughput versus traffic load of the proposed NDMA protocol with sequential detection and non-orthogonal training sequences.

Fig. 2 shows the throughput performance of the proposed protocol for different values of SNR (in dBs) and different values of traffic load (p). The figure also shows the case of the conventional NDMA protocol without sequential detection and with orthogonal training sequences. The results have been obtained for a network of $J = 16$ terminals with a set of non-orthogonal training sequences with $\delta_j = J$ and $\delta_{j,k}$ modeled as a uniform random variable in the range $0 < u < 4$. The terminal presence detection thresholds $\beta_n = n\beta_1$ were calculated considering a probability of false alarm in the first time slot of $P_{F,1} = 0.01$.

The results show that the throughput performance increases for higher values of traffic load, mainly due to the sequential detection mechanism. The more retransmissions available to perform the detection, the more accurate the detection mechanism becomes. The effects of interference due to non orthogonal training sequences can be mainly observed at medium traffic loads, where there is a temporary decrease of throughput. Higher traffic loads means that multiple access interference is also increased. The gains of the sequential detection mechanism seem to overcome in some cases the interference created by non orthogonal training sequences, and therefore the proposed NDMA system can become a good candidate for future 5G access mechanisms due to the flexibility of non orthogonal training sequence allocation, simplified feedback, and the high throughput performance. There is a lot of future work regarding threshold optimisation for terminal detection and also the modeling of different types of non-orthogonal training sequences. The results presented here only display the detector throughput performance. There is a need to extend the analysis as future work to the evaluation of the effects in channel estimation and source separation.

V. Conclusions

This paper has presented the detection analysis of the NDMA protocol under two additional mechanisms: non-orthogonal training sequences, and sequential terminal detection. The first feature aims to make training sequence allocation more flexible and adequate for the hundreds and thousands of objects to request network access. It is shown in this paper that the impact of multiple access interference in NDMA due to the non orthogonal sequence allocation, can be counteracted by the sequential detection mechanism that uses all the received copies of the contending signals. This is an important results to realize the next generation of multiple access protocols with high scalability, low access delay, reduced signalling feedback, and high throughput performance.

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