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Cross-Layer Scheduling Design for OFDMA Two-Way Amplify-and-Forward Relay Networks

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***Abstract*— In this paper, cross-layer scheduling for orthogonal frequency division multiple access (OFDMA) two-way half-duplex amplify-and-forward (AF) relay assisted networks is studied. Assuming slow fading channels, cross-layer scheduling design with imperfect channel state information at the transmitter (CSIT) and heterogeneous data rate requirements for the users is modeled as an optimization problem, where the rate, power, and subcarrier allocation policies are optimized to maximize the system goodput (bit/s/Hz successfully received). The optimization problem is solved by using dual decomposition and a distributed resource allocation algorithm is derived. Simulation results illustrate that our proposed distributed cross-layer scheduler achieves practically the same performance as the optimal centralized scheduler after a small number of iterations.**

I. Introduction

Cooperative communication for wireless networks has received considerable interest [1], [2], as it provides coverage extension, diversity gains, and throughput gains. A particularly interesting approach is two-way half-duplex relaying which achieves higher power and spectral efficiencies compared to one-way half-duplex relaying, by allowing simultaneous message exchanges between a base station (BS) and users. In the literature, different protocols, such as amplify-and-forward (AF) and decode-and-forward (DF), have been proposed to facilitate two-way relaying. AF is particularly appealing as the relays are transparent to the adaptive modulation techniques that are typically employed at the BS. On the other hand, orthogonal frequency division multiple access (OFDMA) is a promising candidate for high speed wireless communication systems, such as WiMAX and Fourth Generation (4G) networks, not only because of its flexibility in resource allocation, but also because of its ability to exploit multiuser diversity. Recently, research in combining OFDMA/OFDM with two-way relaying has drawn much attention. In [3], [4], best effort resource allocation for two-way relay OFDMA and OFDM systems for homogeneous users is studied. In these works, perfect global channel state information (CSI) of individual links is assumed to be available at the BS such that optimal resource allocation can be performed. However, in practice, users are heterogeneous with different quality of service (QoS) requirements, such as outage probability and minimum data rate, which best effort resource allocation cannot guarantee. Besides, perfect CSI at the transmitter (CSIT) cannot be achieved in practice for the relay-to-user links due to the mobility of the users. Furthermore, existing works such as [3]-[5] focus on centralized resource allocation at the BS. As the numbers of users, relays, and subcarriers in the system increase, the overhead of CSI feedback becomes significant and the computational complexity increases exponentially at the BS which limits the scalability of the system in practice. Therefore, distributed resource allocation algorithms, which take into account imperfect CSIT and heterogeneous QoS requirements and converge fast to the optimal solution, are needed for practical implementation.

In this paper, we formulate the scheduling problem in AF two-way half-duplex relay assisted OFDMA systems as an optimization problem. By using dual decomposition, the problem is separated into one master problem and several subproblems. Each relay solves its own subproblem by utilizing its local CSI without any help from other relays while the BS solves the master problem and updates the dual variables through the concept of pricing. Therefore, the computational complexity at the BS and the CSI feedback overhead are both significantly reduced compared to optimal centralized scheduling.

The rest of the paper is organized as follows. In Section II, we outline the model for the considered OFDMA AF two-way relay assisted system. In Section III, we formulate the cross-layer design as an optimization problem, and we solve this problem by dual decomposition in Section IV. Section V presents numerical performance results for the distributed algorithm. In Section VI, we conclude with a brief summary of our results.

II. Two-Way Relay OFDMA network model

We consider an OFDMA two-way relay assisted packet transmission network which consists of one BS, M relays, and K mobile users which belong to one of two categories, namely, *delay sensitive* users and *non-delay sensitive* users. All transceivers are equipped with single antennas. We assume that a direct transmission between the BS and the users is impossible due to heavy blockage. We adopt the frame structure of IEEE 802.16m [6] where a superframe is divided into N frames. Scheduling and resource allocation are performed at the beginning of each superframe. In each frame, the information exchange between the BS and the users via the relays is accomplished in two phases. In the first phase, the BS and users transmit their signals to the relay stations through a multiple access channel. Then, in the second phase, the relay stations amplify the previously received signals and forward them to the corresponding receivers.

A. OFDMA Relay Channel Model

The channel impulse response is assumed to be time-invariant (slow fading) within a frame. We consider an OFDMA system with n_F subcarriers. In the first phase of frame $t \in \{1 \ldots, N\}$, the (frequency domain) received symbol in subcarrier $i \in \{1, \ldots, n_F\}$ at relay $m \in \{1, \ldots, M\}$ for user $k \in \{1, \ldots, K\}$ is given by

$$\begin{aligned} Y_{R_m,i}^{(t,k)} &= \sqrt{P_{BR_m,i}^{(t,k)} l_{BR_m}^{(t)}} H_{BR_m,i}^{(t)} X_i^{(t,k)} \\ &\quad + \sqrt{P_{UR_m,i}^{(t,k)} l_{UR_m}^{(t,k)}} H_{UR_m,i}^{(t,k)} W_i^{(t,k)} + Z_{R_m,i} \quad (1) \end{aligned}$$

where $P_{BR_m,i}^{(t,k)}$ and $X_i^{(t,k)}$ are the transmit power and symbol for the link between the BS and relay m in subcarrier i in the

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first phase of frame t, respectively. $l^{(t)}_{BR_m}$ represents the path loss between the BS and relay m. Variables $P^{(t,k)}_{UR_m,i}$, $W^{(t,k)}_i$, and $l^{(t,k)}_{UR_m}$ are defined in a similar manner as the corresponding variables for the BS-to-relay link except that the signalling direction is from user k to relay m. $Z_{R_m,i}$ is the additive white Gaussian noise (AWGN) in subcarrier i at relay m. $H^{(t)}_{BR_m,i}$ and $H^{(t,k)}_{UR_m,i}$ are the small scale fading coefficients between the BS and relay m and between relay m and user k in subcarrier i, respectively. In practice, both the BS and the relays are placed in relatively high positions and thus the number of blockages and scatterers between them are limited and a strong line of sight is expected. Hence, $H^{(t)}_{BR_m,i}$ is modeled as Rician fading with Rician factor κ, i.e., $H^{(t)}_{BR_m,i} \sim \mathcal{CN}(\sqrt{\kappa/(1+\kappa)}, 1/(1+\kappa))$, where $\mathcal{CN}(\mu, \sigma^2)$ denotes a complex Gaussian random variable with mean μ and variance σ^2. On the other hand, since the users are generally surrounded by a large number of scatterers, we model $H^{(t,k)}_{UR_m,i}$ as Rayleigh distributed, i.e., $H^{(t,k)}_{UR_m,i} \sim \mathcal{CN}(0, 1)$.

The received signals at relay m in subcarrier i from the BS and user k, respectively, are mapped to subcarrier $p \in \{1, \ldots, n_F\}$ in the second phase in order to optimize performance [4]. Furthermore, the signal in subcarrier p is forwarded to the destinations after being amplified by a gain factor $\sqrt{G^{(t,k)}_{R_m,i,p} P^{(t,k)}_{R_m,p}}$, where $P^{(t,k)}_{R_m,p}$ is the transmit power of relay m in subcarrier p for user k and the BS, and $G^{(t,k)}_{R_m,i,p}$ normalizes the input power of the relay. Since the channel is time invariant for the two transmission phases, channel reciprocity is preserved. Therefore, the signal received at user k in subcarrier p from relay m in frame t is given by

$$\tilde{Y}^{(t,k)}_{U_m,p} = \sqrt{G^{(t,k)}_{R_m,i,p} P^{(t,k)}_{R_m,p} l^{(t,k)}_{UR_m}} H^{(t,k)}_{UR_m,p} \times \left(\sqrt{P^{(t,k)}_{BR_m,i} l^{(t)}_{BR_m}} H^{(t)}_{BR_m,i} X^{(t,k)}_i + I^{(t,k)}_{m,i} + Z_{R_m,i} \right) + Z^{(k)}_p \quad (2)$$

where $I^{(t,k)}_{m,i} = \sqrt{P^{(t,k)}_{UR_m,i} l^{(t,k)}_{UR_m}} H^{(t,k)}_{UR_m,i} W^{(t,k)}_i$ represents the *self-interference* of user k and $Z^{(k)}_p$ is the AWGN at user k in subcarrier i. For simplicity and without loss of generality, we assume in the following a normalized noise variance of $N_0 = 1$ at all transceivers. By estimating the training sequences in each frame and using the channel reciprocity, the *self-interference* is perfectly known at user k and can be subtracted from $\tilde{Y}^{(t,k)}_{U_m,p}$ [1]. Therefore, the received signal after self-interference cancellation can be written as

$$Y^{(t,k)}_{U_m,p} = \sqrt{G^{(t,k)}_{R_m,i,p} P^{(t,k)}_{R_m,p} l^{(t,k)}_{UR_m}} H^{(t,k)}_{UR_m,p} \times \left(\sqrt{P^{(t,k)}_{BR_m,i} l^{(t)}_{BR_m}} H^{(t)}_{BR_m,i} X^{(t,k)}_i + Z_{R_m,i} \right) + Z^{(k)}_p. \quad (3)$$

Similarly, the received signal at the BS in subcarrier p from user k is given by

$$Y^{(t,k)}_{B_m,p} = \sqrt{G^{(t,k)}_{R_m,i,p} P^{(t,k)}_{R_m,p} l^{(t)}_{BR_m}} H^{(t)}_{BR_m,p} \times \left(\sqrt{P^{(t,k)}_{UR_m,i} l^{(t,k)}_{UR_m}} H^{(t,k)}_{UR_m,i} W^{(t,k)}_i + Z_{R_m,i} \right) + Z_p \quad (4)$$

where Z_p is the AWGN at the BS in subcarrier p. Following [1], the gain is chosen as $|G^{(t,k)}_{R_m,i,p}|^{-1} =$

$$1 + P^{(t,k)}_{BR_m,i} l^{(t)}_{BR_m} |H^{(t)}_{BR_m,i}|^2 + P^{(t,k)}_{UR_m,i} l^{(t,k)}_{UR_m} |H^{(t,k)}_{UR_m,i}|^2. \quad (5)$$

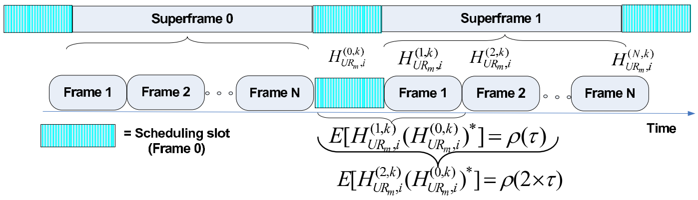

Fig. 1. Frame structure and CSI correlation model.

B. Channel State Information

In the considered system, both the BS and the users exchange information with the help of relays. As mentioned before, we assume the CSI of all links to be constant for the duration of one frame. Thus, the BS, the relays, and all (scheduled) users can accurately estimate the CSI of their links using training symbols in each frame for relaying and signal detection purposes. For scheduling we assume that the relays perfectly know the path losses of their respective BS-to-relay and relay-to-user links due to accurate long term measurements. Furthermore, to perform scheduling for the next superframe, the relays estimate the small scale fading coefficients of their respective BS-to-relay and relay-to-user links based on training symbols sent by the BS and all users at the beginning of the scheduling slot, cf. Figure 1. Since we assume that both the BS and the relays are static, the associated channel is time-invariant and is assumed to remain constant for the duration of the entire superframe. In contrast, due to the mobility of the users, the CSI of the relay-to-user links changes slowly and the CSIT of these links used for scheduling becomes outdated over the duration of a superframe. To capture this effect, we model the CSI of the relay-to-user links by using Jake's model. For simplicity, we assume that each scheduling slot has the length of one frame. As illustrated in Figure 1, the correlation between the scheduling slot (frame 0) and frame t in subcarrier i of the link between relay m and user k is

$$E[H^{(t,k)}_{UR_m,i}(H^{(0,k)}_{UR_m,i})^*] = \rho(t \times \tau), \quad (6)$$

where $E[\cdot]$ and $(\cdot)^*$ denote statistical expectation and complex conjugation, respectively. Furthermore, $\rho(\tau) = J_0(2\pi f_D \tau)$, τ is the time duration of one frame, $J_0(\cdot)$ is the zeroth order Bessel function of the first kind, and f_D is the maximum Doppler frequency. Therefore, for scheduling purposes, the actual CSI in frame $t \in \{1, \ldots, N\}$ for the link between user k and relay m in subcarrier i can be expressed as

$$H^{(t,k)}_{UR_m,i} = \sqrt{1 - \sigma^2_e(t)} \hat{H}^{(t,k)}_{UR_m,i} + \Delta H^{(t,k)}_{UR_m,i}, \quad (7)$$

where $\hat{H}^{(t,k)}_{UR_m,i} = H^{(0,k)}_{UR_m,i}$ is the outdated CSI used for scheduling at the beginning of the superframe. Here, $H^{(0,k)}_{UR_m,i}$ is the actual CSI in the last frame of the previous superframe and $\Delta H^{(t,k)}_{UR_m,i} \sim \mathcal{CN}(0, \sigma^2_e(t))$ represents the CSIT error which is uncorrelated with $H^{(0,k)}_{UR_m,i}$ and has variance $\sigma^2_e(t) = 1 - \rho^2(t \times \tau)$.

III. Cross-Layer Design Problem

A. Instantaneous Mutual Information and System Goodput

Given perfect CSI at the receiver, the downlink (DL) instantaneous channel capacity between the BS and user k in using subcarrier pair (i, p) through relay m in frame t is

$$C^{(t,k)}_{DL_m,i,p} = \frac{1}{2} \log_2(1 + \Gamma^{(t,k)}_{DL_m,i,p}) \quad (8)$$

with equivalent DL signal-to-noise ratio (SNR) $\Gamma^{(t,k)}_{DL_m,i,p} =$

$$\frac{G^{(t,k)}_{R_m,i,p}P^{(t,k)}_{BR_m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2P^{(t,k)}_{R_m,p}l^{(t,k)}_{UR_m}|H^{(t,k)}_{UR_m,p}|^2}{1+G^{(t,k)}_{R_m,i,p}P^{(t,k)}_{R_m,p}l^{(t,k)}_{UR_m}|H^{(t,k)}_{UR_m,p}|^2}. \quad (9)$$

Similarly, the channel capacity for the end-to-end uplink (UL) for user k in using subcarrier pair (i,p) through the m-th relay in frame t is given by

$$C^{(t,k)}_{UL_m,i,p} = \frac{1}{2}\log_2(1+\Gamma^{(t,k)}_{UL_m,i,p}) \quad (10)$$

with equivalent UL SNR $\Gamma^{(t,k)}_{UL_m,i,p} =$

$$\frac{G^{(t,k)}_{R_m,i,p}P^{(t,k)}_{UR_m,i}l^{(t,k)}_{UR_m}|H^{(t,k)}_{UR_m,i}|^2P^{(t,k)}_{R_m,p}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,p}|^2}{1+G^{(t,k)}_{R_m,i,p}P^{(t,k)}_{R_m,p}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,p}|^2}. \quad (11)$$

We first define the system goodput (bit/s/Hz successfully delivered) of DL and UL transmission in one superframe for user k, who is assigned to relay m, as

$$\rho^{(k)}_{DL_m}=\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\frac{s^{(t,k)}_{m,i,p}r^{(t,k)}_{DL_{m,i,p}}}{S_{n_F}}\mathbf{1}(r^{(t,k)}_{DL_m,i,p}\le C^{(t,k)}_{DL_m,i,p})$$
$$\rho^{(k)}_{UL_m}=\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\frac{s^{(t,k)}_{m,i,p}r^{(t,k)}_{UL_{m,i,p}}}{S_{n_F}}\mathbf{1}(r^{(t,k)}_{UL_m,i,p}\le C^{(t,k)}_{UL_m,i,p}) \quad (12)$$

where $S_{n_F} = N\times n_F$, $\mathbf{1}(\cdot)$ is an indicator function which is 1 when the event is true and 0 otherwise, $s^{(t,k)}_{m,i,p}\in\{0,1\}$ is the subcarrier pair allocation indicator, and $r^{(t,k)}_{DL_{m,i,p}}$ and $r^{(t,k)}_{UL_{m,i,p}}$ are the transmission data rates for DL and UL, respectively. The *average weighted system goodput* is defined as the total average bit/s/Hz successfully decoded at the BS and the K mobile stations through the M relays (averaged over multiple scheduling phases) and given by

$$U(\mathcal{P},\mathcal{R},\mathcal{S}) = E\left\{\sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}w^{(k)}(\rho^{(k)}_{DL_m}+\rho^{(k)}_{UL_m})\right\}$$

where $\mathcal{P},\mathcal{R}$, and $\mathcal{S}$ are the power, rate, and subcarrier allocation policies, respectively. $\mathcal{U}_m$ is the set of users associated with relay m and $w^{(k)}$ is a positive constant that can be used to prioritize different users and to enforce certain notions of fairness.

B. Cross-Layer Design Problem Formulation

In practice, a channel outage occurs in slow fading channels whenever the data rate exceeds the channel capacity. Furthermore, users are heterogeneous with different data rate requirements. Therefore, a practical scheduler should be able to fulfill the different data rate requirements of the users as well as their channel outage probability requirements. This leads to the following optimization problem. The optimal power allocation policy, $\mathcal{P}^*$, rate allocation policy, $\mathcal{R}^*$, and subcarrier allocation policy, $\mathcal{S}^*$, are given by

$$(\mathcal{P}^*,\mathcal{R}^*,\mathcal{S}^*) = \arg\max_{\mathcal{P},\mathcal{R},\mathcal{S}} U(\mathcal{P},\mathcal{R},\mathcal{S})$$
$$\text{s.t. C1: } \Pr\left[r^{(t,k)}_{DL_m,i,p} > C^{(t,k)}_{DL_m,i,p}|\mathbf{\Xi}_m\right]\le\varepsilon, \quad \forall k,t$$
$$\text{C2: } \Pr\left[r^{(t,k)}_{UL_m,i,p} > C^{(t,k)}_{UL_m,i,p}|\mathbf{\Xi}_m\right]\le\varepsilon, \quad \forall k,t$$
$$\text{C3: } \sum_{m=1}^{M}\left(\rho^{(k)}_{DL_m}+\rho^{(k)}_{UL_m}\right)\ge R^{(k)}, \quad \forall k\in\mathcal{D}$$
$$\text{C4: } \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}s^{(t,k)}_{m,i,p}P^{(t,k)}_{m,i,p}\le P_T$$
$$\text{C5: } \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{i=1}^{n_F}s^{(t,k)}_{m,i,p}=1, \quad \forall p,t$$
$$\text{C6: } \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{p=1}^{n_F}s^{(t,k)}_{m,i,p}=1, \quad \forall i,t$$
$$\text{C7: } s^{(t,k)}_{m,i,p}\in\{0,1\}, \ \forall m,i,p,k,t$$
$$\text{C8: } P^{(t,k)}_{BR_m,i}, P^{(t,k)}_{UR_m,i}, P^{(t,k)}_{R_m,p}\ge 0, \ \forall m,i,p,k,t \quad (13)$$

where $\mathbf{\Xi}_m = [\mathbf{H}_{BR_m},\mathbf{H}_{UR_m},\mathbf{L}_m]$ is the CSI matrix. $\mathbf{H}_{BR_m}$, $\mathbf{H}_{UR_m}$, and $\mathbf{L}_m$ represent the actual CSI of the link between the BS and relay m from the previous transmission, the CSI of all links from relay m to users $k\in\mathcal{U}_m$, and the path losses of all links involving relay m, respectively. In C1 (C2), ε represents the target outage probability of the DL (UL) for user k in each frame. $R^{(k)}$ in C3 is the minimum required data rate for the *delay sensitive* users. In C4, $\mathcal{D}$ is a set of *delay sensitive* users and $P^{(t,k)}_{m,i,p} = P^{(t,k)}_{UR_m,i}+P^{(t,k)}_{BR_m,i}+P^{(t,k)}_{R_m,p}$ is the total power usage of the BS, the relays, and the users for one subcarrier pair (i,p). The total maximum power consumed across all subcarrier pairs is limited by the maximum power P_T. C5, C6, and C7 are imposed to guarantee that each subcarrier pair is used by only one user in each frame.

IV. Solution of the Optimization Problem

A. Transformation of the Optimization Problem

The two-way relay cross-layer scheduling problem in (13) is a mixed combinatorial and non-convex optimization problem which requires brute force to obtain the globally optimal solution. Unfortunately, such an approach does not provide useful system design insight and is computationally infeasible. In order to obtain an insightful closed-form solution and to overcome the non-convexity of the problem, we assume that the transmitted power of DL and UL can be expressed as

$$P^{(t,k)}_{BR_m,i} = \alpha^{(t,k)}_{m,i}P^{(t,k)}_{(B+U)_m,i}, P^{(t,k)}_{UR_m,i} = (1-\alpha^{(t,k)}_{m,i})P^{(t,k)}_{(B+U)_m,i},$$
$$P^{(t,k)}_{(B+U)_m,i} = P^{(t,k)}_{BR_m,i}+P^{(t,k)}_{UR_m,i}, \quad (16)$$

where $0<\alpha^{(t,k)}_{m,i}<1$ controls the transmit power ratio between UL and DL, and $P^{(t,k)}_{(B+U)_m,i}$ is the power consumption on subcarrier i by the BS and user k. Furthermore, it can be shown that, at high SNR, the system goodput is dominated by the cut-set bound [2], and thus the power allocation for BS, relay m, and user k in using subcarrier pair (i,p) in frame t is given by

$$P^{(t,k)}_{R_m,p} = \frac{P^{(t,k)}_{m,i,p}}{2}, \qquad P^{(t,k)}_{(B+U)_m,i}=\frac{P^{(t,k)}_{m,i,p}}{2}, \quad (17)$$
$$P^{(t,k)}_{UR_m,i}=\frac{(1-\alpha^{(t,k)}_{m,i})P^{(t,k)}_{m,i,p}}{2}, P^{(t,k)}_{BR_m,i} = \frac{\alpha^{(t,k)}_{m,i}P^{(t,k)}_{m,i,p}}{2}$$

i.e., the relay consumes the same amount of power as the BS and the user combined. The proof of (17) is omitted due to page limitation. $P^{(t,k)}_{m,i,p}$ is now the new optimization variable for power allocation. The next step to solve problem (13) is to incorporate the outage probability constraints in C1 and C2 into the objective function. This is possible if the constraints in C1 and C2 are fulfilled with equality for the optimal solution, which

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$$\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p} = \frac{P^{(t,k)}_{m,i,p}(1-\alpha^{(t,k)}_{m,i})l^{(t,k)}_{UR_m}F^{-1(t,k)}_{UR_m,i}(\varepsilon)l^{(t)}_{BR_m}|H^{(t)}_{BR_m,p}|^2}{2\left(\alpha^{(t,k)}_{m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2+(1-\alpha^{(t,k)}_{m,i})l^{(t,k)}_{UR_m}F^{-1(t,k)}_{UR_m,i}(\varepsilon)+l^{(t)}_{BR_m}|H^{(t)}_{BR_m,p}|^2\right)}, \forall i,p \quad (20)$$

$$\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p} = \begin{cases} \frac{P^{(t,k)}_{m,i,p}\alpha^{(t,k)}_{m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2 l^{(t,k)}_{UR_m}F^{-1(t,k)}_{UR_m,i}(\varepsilon)}{2\left(\alpha^{(t,k)}_{m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2+(2-\alpha^{(t,k)}_{m,i})l^{(t,k)}_{UR_m}F^{-1(t,k)}_{UR_m,i}(\varepsilon)\right)} & \text{if } i=p \\ \frac{P^{(t,k)}_{m,i,p}\alpha^{(t,k)}_{m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2(F^{-1(t,k)}_{UR_m,i,p}(\varepsilon))^2}{2\left(\alpha^{(t,k)}_{m,i}l^{(t)}_{BR_m}|H^{(t)}_{BR_m,i}|^2+(F^{-1(t,k)}_{UR_m,i,p}(\varepsilon))^2\right)} & \text{if } i\neq p \end{cases} \quad (21)$$

is the case for the low outage probabilities typically required in practical applications (e.g. $\varepsilon \leq 0.01$). Thus, in the following we replace the "$\leq$"-sign in C1 (C2) by a "$=$"-sign. We are now ready to introduce the following Lemma.

Lemma 1 (Equivalent Rate Constraint): For a given outage probability ε in C2 and C1, the equivalent rates $r^{(t,k)}_{UL_m,i,p}$ and $r^{(t,k)}_{DL_m,i,p}$ in high SNR are

$$\text{C2} \Rightarrow r^{(t,k)}_{UL_m,i,p} = \frac{1}{2}\log_2\left(1+\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p}\right) \quad (18)$$

$$\text{C1} \Rightarrow r^{(t,k)}_{DL_m,i,p} = \frac{1}{2}\log_2\left(1+\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p}\right) \quad (19)$$

where $\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p}$ and $\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p}$ are defined in (20) and (21) at the top of this page, respectively. $F^{-1(t,k)}_{UR_m,i}(\varepsilon)$ in (20) and (21) is the inverse cumulative distribution function (c.d.f.) of a non-central chi-square random variable with 2 degrees of freedom and non-centrality parameter $\frac{|\hat{H}^{(t,k)}_{UR_m,i}|^2}{\sigma^2_e(t)}$, where $\sigma^2_e(t)$ is given in (7). $F^{-1(t,k)}_{UR_m,i,p}(\varepsilon)$ in (21) is the inverse c.d.f. of a random variable which is the ratio of two independent non-identical Rice distributed random variables, cf. (30).

Proof: Please refer to the Appendix. □

By substituting (18) and (19) into the original objective function in (13), a new objective function which incorporates outage can be obtained.

To handle the combinatorial subcarrier allocation problem, we follow the approach in [7] and relax $s^{(t,k)}_{m,i,p}$ in constraint C7 to a real value between zero and one. Then, $s^{(t,k)}_{m,i,p}$ can be interpreted as a time sharing factor for the K users to utilize subcarrier pair (i,p). Furthermore, since the power constraint is instantaneous, average weighted system goodput maximization is identical to the maximization of the instantaneous weighted goodput. Thus, we can rewrite problem (13) as

$$\arg\max_{\mathcal{P},\mathcal{R},\mathcal{S}} \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\frac{w^{(k)}s^{(t,k)}_{m,i,p}}{2S_{n_F}}C^{(t,k)}_{m,i,p}$$

$$\text{s.t. C4:} \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\underbrace{\tilde{P}^{(t,k)}_{(B+U)_m,i}+\tilde{P}^{(t,k)}_{R_m,p}}_{\tilde{P}^{(t,k)}_{m,i,p}} \leq P_T$$

$$\text{C3,} \quad \text{C5,} \quad \text{C6,} \quad \text{C8}$$

$$\text{C7: } 0 \leq s^{(t,k)}_{m,i,p} \leq 1, \qquad \forall m,i,p,t,k \quad (22)$$

where $C^{(t,k)}_{m,i,p} = \log_2(1+\frac{\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p}}{s^{(t,k)}_{m,i,p}}) + \log_2(1+\frac{\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p}}{s^{(t,k)}_{m,i,p}})$ and $\tilde{P}^{(t,k)}_{(B+U)_m,i} = s^{(t,k)}_{m,i,p}P^{(t,k)}_{(B+U)_m,i}$, $\tilde{P}^{(t,k)}_{R_m,p} = s^{(t,k)}_{m,i,p}P^{(t,k)}_{R_m,p}$, $\tilde{P}^{(t,k)}_{m,i,p} = s^{(t,k)}_{m,i,p}P^{(t,k)}_{m,i,p}$, and $\tilde{P}^{(t,k)}_{m,i,p} = \tilde{P}^{(t,k)}_{(B+U)_m,i} + \tilde{P}^{(t,k)}_{R_m,p}$ are auxiliary power variables. The new problem is now jointly concave with respect to the optimization variables, and thus, solving the dual problem is equivalent to solving the original primal problem [8].

B. Dual Problem Formulation

In this subsection, we formulate the dual for the considered cross-layer scheduling optimization problem. For this purpose, we first need the Lagrangian function of the primal problem. Upon rearranging terms, the Lagrangian can be written as

$$\begin{aligned}&\mathcal{L}(\lambda,\boldsymbol{\beta},\boldsymbol{\delta},\boldsymbol{\upsilon},\mathcal{P},\mathcal{R},\mathcal{S})\\ &=\sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\frac{s^{(t,k)}_{m,i,p}(w^{(k)}+\delta_k)}{2S_{n_F}}C^{(t,k)}_{m,i,p}+\lambda P_T\\ &-\lambda\sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\tilde{P}^{(t,k)}_{m,i,p}+\sum_{t=1}^{N}\sum_{i=1}^{n_F}(\beta^{(t)}_i+\upsilon^{(t)}_i)\\ &-\sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}(\beta^{(t)}_p+\upsilon^{(t)}_i)s^{(t,k)}_{m,i,p}-\sum_{k=1}^{K}R^{(k)}\delta_k \quad (23)\end{aligned}$$

where λ is the Lagrange multiplier corresponding to the joint power constraint. $\boldsymbol{\delta}$ is the vector of Lagrange multipliers whose elements are δ_k, $k \in \mathcal{D}$, for the *delay sensitive users* and equal to zero for the *non-delay sensitive* users. Lagrange multiplier vectors $\boldsymbol{\beta}$ and $\boldsymbol{\upsilon}$ are associated with the subcarrier usage constraints and have elements $\beta^{(t)}_p$, $p \in \{1,\ldots,n_F\}$ and $\upsilon^{(t)}_i$, $i \in \{1,\ldots,n_F\}$, $t \in \{1,\ldots,N\}$, respectively. Thus, for $m \in \{1,\cdots,M\}$ the dual problem is given by

$$\min_{\lambda,\boldsymbol{\beta},\boldsymbol{\delta},\boldsymbol{\upsilon}\geq 0}\ \max_{\mathcal{P},\mathcal{R},\mathcal{S}} \quad \mathcal{L}_m(\lambda,\boldsymbol{\beta},\boldsymbol{\delta},\boldsymbol{\upsilon},\mathcal{P},\mathcal{R},\mathcal{S}) \quad (24)$$

where $\mathcal{L}_m(\lambda,\boldsymbol{\beta},\boldsymbol{\delta},\boldsymbol{\upsilon},\mathcal{P},\mathcal{R},\mathcal{S}) =$

$$\begin{aligned}&\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\left(\frac{s^{(t,k)}_{m,i,p}(w^{(k)}+\delta_k)}{2S_{n_F}}C^{(t,k)}_{m,i,p}-\lambda\tilde{P}^{(t,k)}_{m,i,p}\right)\\ &-\sum_{k\in\mathcal{U}_m}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\sum_{t=1}^{N}(\beta^{(t)}_p+\upsilon^{(t)}_i)s^{(t,k)}_{m,i,p}. \quad (25)\end{aligned}$$

C. Distributed Solution - Subproblem for Each Relay Station

By dual decomposition, the dual problem in (24) can be decomposed into a master problem and serval subproblems. The dual problem can be solved iteratively where in each iteration each relay solves one local subproblem without any assistance from the other relays and passes its local solution on to the BS which solves the master problem. The subproblem to be solved by relay m is given by

$$\max_{\mathcal{P},\mathcal{R},\mathcal{S}} \quad \mathcal{L}_m(\lambda,\boldsymbol{\beta},\boldsymbol{\delta},\boldsymbol{\upsilon},\mathcal{P},\mathcal{R},\mathcal{S})$$

where the Lagrange multipliers $\boldsymbol{\lambda},\boldsymbol{\beta},\boldsymbol{\delta}$, and $\boldsymbol{\upsilon}$ are provided by the BS at the end of each iteration. Using standard optimization techniques and the Karush-Kuhn-Tucker (KKT) condition, the optimal power allocation in high SNR for using subcarrier pair

(i, p) can be shown to be

$$\tilde{P}^{*(t,k)}_{m,i,p} = s^{(t,k)}_{m,i,p}\left(\frac{(w^{(k)}+\delta_k)}{\lambda} - \frac{\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p}+\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p}}{2\Lambda^{(t,k)}_{\mathrm{UL}_m,i,p}\Lambda^{(t,k)}_{\mathrm{DL}_m,i,p}}\right)^+ \quad (26)$$

where $(x)^+ = \max\{0, x\}$. The optimal values of $P^{*(t,k)}_{R_m,p}$, $P^{*(t,k)}_{BR_m,i}$, and $P^{*(t,k)}_{UR_m,i}$ can be calculated by applying (26) in (17). In order to obtain the optimal subcarrier allocation, we take the derivative of the subproblem with respect to $s^{(t,k)}_{m,i,p}$, i.e., $\frac{\partial \mathcal{L}_m}{\partial s^{(t,k)}_{m,i,p}} = 0$, and the subcarrier pair selection determined by relay m is given by

$$s^{*(t,k)}_{m,i,p} = \begin{cases} 1 & \text{if } \tilde{C}^{*(t,k)}_{m,i,p} \geq \frac{2(\beta^{(t)}_p + \upsilon^{(t)}_i)}{w^{(k)}+\delta_k} + 2 \\ 0 & \text{otherwise} \end{cases} \quad (27)$$

in high SNR, where $\tilde{C}^{*(t,k)}_{m,i,p} = \tilde{C}^{(t,k)}_{m,i,p}|_{\tilde{P}^{(t,k)}_{m,i,p}=\tilde{P}^{*(t,k)}_{m,i,p}}$. The dual variables $\beta^{(t)}_p + \upsilon^{(t)}_i$ act as the price in using the subcarrier pair (i, p) in frame t. Only the user who has good enough channel conditions in subcarrier pair (i, p) is able to pay the price and is selected by the scheduler. Furthermore, variable δ_k forces the scheduler to assign more subcarrier pairs to *delay sensitive* users by lowering the price. Finally, the optimal rate allocations $r^{*(t,k)}_{DL_m,i,p}$ and $r^{*(t,k)}_{UL_m,i,p}$ are obtained by substituting (17) and (26) into the equivalent packet outage constraint in (18) and (19) for the subcarrier pairs with $s^{(t,k)}_{m,i,p} = 1$.

D. Solution of the Master Dual Problem at the BS

For solving the master problem at the BS, each relay calculates the local resource usages and passes this information, i.e., $r^{*(t,k)}_{DL_m,i,p}, r^{*(t,k)}_{UL_m,i,p}, s^{*(t,k)}_{m,i,p}$, and $P^{*(t,k)}_{m,i,p}$, to the BS. Since the dual function is differentiable, the gradient method can be used to solve the minimization in (24) at the BS. Thus, in iteration n the BS updates the dual variables as

$$\beta^{(t)}_p(n+1) = \left[\beta^{(t)}_p(n) - \xi_1(n)\Big(1 - \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{i=1}^{n_F} s^{(t,k)}_{m,i,p}\Big)\right]^+, \forall p, t$$

$$\upsilon^{(t)}_i(n+1) = \left[\upsilon^{(t)}_i(n) - \xi_2(n)\Big(1 - \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{p=1}^{n_F} s^{(t,k)}_{m,i,p}\Big)\right]^+, \forall i, t$$

$$\delta_k(n+1) = \left[\delta_k(n) - \xi_3(n)\big(\Delta R^{(k)}\mathbf{1}(\Delta R^{(k)}<0)\big)\right]^+, \forall k \in \mathcal{D}$$

$$\lambda(n+1) = \Bigg[\lambda(n) - \xi_4(n) \times \Bigg(P_T - \sum_{m=1}^{M}\sum_{k\in\mathcal{U}_m}\sum_{t=1}^{N}\sum_{i=1}^{n_F}\sum_{p=1}^{n_F}\tilde{P}^{(t,k)}_{m,i,p}\Bigg)\Bigg]^+ \quad (28)$$

where $\Delta R^{(k)}$ is the difference between scheduled data rate and target data rate for *delay sensitive* user k, i.e., $\Delta R^{(k)} = \sum_{m=1}^{M}\left(\rho^{(k)}_{DL_m} + \rho^{(k)}_{UL_m}\right) - R^{(k)}$. $\xi_1(n), \xi_2(n), \xi_3(n)$, and $\xi_4(n)$ are positive step sizes. Combining (28) with (27), each selected subcarrier pair will be occupied by one user only. We observe from (26)–(28) that relay m, $m \in \{1, \ldots, M\}$, only requires the CSI of its own BS-to-relay link, the imperfect CSI of the relay-to-user links of the associated users, and the dual variables λ, $\beta^{(t)}_p$, $p \in \{1, \ldots, n_F\}$, $\upsilon^{(t)}_i$, $i \in \{1, \ldots, n_F\}$, $t \in \{1, \ldots, N\}$, and δ_k, $k \in \mathcal{D}$, supplied by the BS in each iteration.

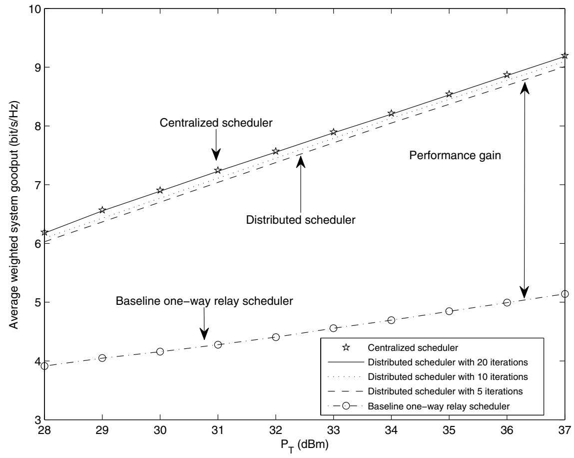

Fig. 2. Average weighted system goodput versus total transmit power for different scheduling algorithms with user mobilities of 5 km/h.

V. Results and Discussions

In this section, we evaluate the system performance using simulations. A single cell with two ring-shaped boundary regions is considered. The outer boundary has a radius of 1 km and the inner boundary a radius of 500 m. There are 3 relay stations equally distributed at the inner cell boundary for assisting the transmission and K active users uniformly distributed in the outer ring. In a superframe, there are $N = 5$ frames, each of which has a length of 2 ms. The number of subcarriers is $n_F = 64$ with carrier center frequency 2.5 GHz, and $w_k = 1, \forall k$. The 3GPP path loss model is used [9]. The small scale fading coefficients of the BS-to-relay links are generated as independent and identically distributed (i.i.d.) Rician random variables with $\kappa = 6$ dB, while the small scale fading coefficients of the relay-to-user links are i.i.d. Rayleigh fading. $\alpha^{(t,k)}_{m,i} = 2/3$ such that the transmit power of the BS is twice that of the mobile users. The target outage probability ε is set to 1%. The average system goodput is obtained by counting the number of packets which are successfully decoded by the BS and the users averaged over both macroscopic and microscopic fading.

A. System Goodput versus Transmit Power

Figure 2 illustrates the average weighted system goodput versus the total transmit power P_T for $K = 15$ users with mobilities of 5 km/h. In the cell, there are 3 *delay sensitive* users with data rate requirement $R^{(k)} = 2$ bit/s/Hz, $k \in \mathcal{D}$, while the remaining users are *non-delay sensitive*. The performance of the proposed distributed scheduling algorithm with 5, 10, and 20 iterations is compared with the optimal centralized scheduling algorithm and a baseline one-way half-duplex relay scheduler for the same target outage probability for all users. For the centralized scheduler, the BS uses the global CSI of each link to perform an exhaustive search to find the optimal subcarrier allocation and uses a standard *multi-level water-filling* procedure to obtain the optimal power allocation and rate adaption. It can be seen that the performance difference between the two schedulers is negligible after a small number of iterations which confirms the practicality of our proposed distributed scheduling algorithm. On the other hand, the proposed scheduler achieves a substantial gain in system goodput when compared with the baseline scheme, especially in the high transmit power regime. This is because the proposed scheduler has a better

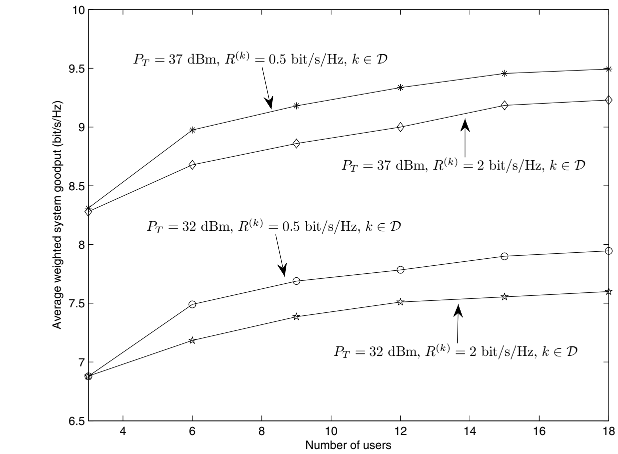

Fig. 3. Average weighted system goodput versus number of users with different data rate requirements and transmit powers at user mobilities of 5 km/h.

spectral efficiency by utilizing simultaneous message exchanges between BS and users.

B. System Goodput versus Number of Users

Figure 3 depicts the average weighted system goodput versus the number of users with different transmit power and user data rate requirements. All users in the system have a mobility of 5 km/h and there are 3 *delay sensitive* users. The number of iterations for the distributed scheduler is 20. It can be observed that the system goodput grows with the number of users due to *multi-user diversity* (MUD). However, the MUD gain diminishes as the data rate requirements become more stringent since most of the resources are taken by the *delay sensitive* users regardless of the actual channel quality. On the contrary, the *non-delay sensitive* users can not be served even if they have very good channel conditions, because the scheduler needs to fulfill the data rate requirements of the *delay sensitive* users.

VI. Conclusion

In this paper, we formulate the cross-layer scheduling design for two-way half-duplex AF relay assisted OFDMA systems as a mixed combinatorial and non-convex optimization problem, in which imperfect CSIT and heterogeneous user QoS requirements are taken into consideration. By assuming high SNR and relaxing the subcarrier allocation constraints, the considered problem can be transformed into a convex problem. A distributed scheduling algorithm is derived based on dual decomposition, which requires only local CSIT at each relay. Simulation results show that the performance of the distributed algorithm approaches the optimal centralized scheduler in a small number of iterations which confirms the practicality and scalability of the proposed scheduler.

Appendix-Proof of Lemma 1

For the UL data rate $r_{UL_m,i,p}^{(t,k)}$, we only provide a sketch of the proof due to page limitation. We start by calculating the outage probability in C2 in (13). Since the CSI of the BS-to-relay link is available at the scheduler, the only randomness is due to the imperfect CSIT of the relay-to-user links. Thus, the outage probability can be written as a function of the c.d.f. of a non-central chi-square random variable with 2 degrees of freedom and non-centrality parameter $\frac{|\hat{H}_{UR_m,i}^{(t,k)}|^2}{\sigma_e^2(t)}$. Then, by equating the c.d.f. with the required outage probability ε and solving for $r_{UL_m,i,p}^{(t,k)}$, (18) follows immediately.

For the DL data rate $r_{DL_m,i,p}^{(t,k)}$, we need to first derive the probability density function of the outage event. For the case of $i = p$, since there is only one random variable in the view of the scheduler, we can follow the same approach as for the UL data rate. For the case of $i \neq p$, we define random variables $X_{m,p}^{(t,k)} = |H_{UR_m,p}^{(t,k)}|^2$ and $Y_{m,i}^{(t,k)} = |H_{UR_m,i}^{(t,k)}|^2$ which are non-central chi-square distributed with 2 degrees of freedom, non-centrality parameters $s_x^2 = |\hat{H}_{UR_m,p}^{(t,k)}|^2$ and $s_y^2 = |\hat{H}_{UR_m,i}^{(t,k)}|^2$, and variances σ_x^2 and σ_y^2, respectively. Conditional on the CSI matrix $\mathbf{\Xi}_m$, upon rearranging terms, the outage probability of the DL transmission is given by

$$\Pr\left(A_{m,i,p}^{(t,k)}/B_{m,i,p}^{(t,k)} < \sqrt{\ell_{m,i}^{(t,k)}\eta_{m,i,p}^{(t,k)}/(\ell_{m,i}^{(t,k)} - \eta_{m,i,p}^{(t,k)})}\right) \quad (29)$$

where $A_{m,i,p}^{(t,k)} = \sqrt{\ell_{m,i}^{(t,k)}\, l_{UR_m}^{(t,k)} X_{m,p}^{(t,k)}}$, $B_{m,i,p}^{(t,k)} = \sqrt{\ell_{m,i}^{(t,k)} + \theta_{m,i}^{(t,k)} Y_{m,i}^{(t,k)}}$, $\ell_{m,i}^{(t,k)} = \alpha_{m,i}^{(t,k)} l_{BR_m}^{(t)} |H_{BR_m,i}^{(t)}|^2$, $\eta_{m,i,p}^{(t,k)} = (2^{2r_{DL_m,i,p}^{(t,k)}} - 1)\frac{2}{P_{m,i,p}^{(t,k)}}$, and $\theta_{m,i}^{(t,k)} = (1 - \alpha_{m,i}^{(t,k)}) l_{UR_m}^{(t,k)}$. Note that in (29) $\ell_{m,i}^{(t,k)} > \eta_{m,i,p}^{(t,k)}$ as $r_{DL_m,i,p}^{(t,k)}$ will not exceed the channel capacity of the BS-relay links since the corresponding perfect CSI is available at the schedulers. Let $Z_{UR_m,i,p}^{(t,k)} = \frac{A_{m,i,p}^{(t,k)}}{B_{m,i,p}^{(t,k)}}$, where $A_{m,i,p}^{(t,k)}$ and $B_{m,i,p}^{(t,k)}$ are Rician random variables with 2 degrees of freedom, non-centrality parameters $s_a^2 = \ell_{m,i}^{(t,k)} l_{UR_m}^{(t,k)} s_x^2$ and $s_b^2 = \ell_{m,i}^{(t,k)} + \theta_{m,i}^{(t,k)} s_y^2$, and variances $\sigma_a^2 = (\ell_{m,i}^{(t,k)} l_{UR_m}^{(t,k)})^2 \sigma_x^2$ and $\sigma_b^2 = (\theta_{m,i}^{(t,k)})^2 \sigma_y^2$, respectively. Thus, the c.d.f. of $Z_{UR_m,i,p}^{(t,k)}$, which is a ratio of two independent non-identical Rice distributed random variables, is [10]

$$F_{UR_m,i,p}^{(t,k)}(z) = Q(c,d) - \frac{\sigma_a^2 c^2}{s_b^2 z^2}\exp\left(-\frac{c^2+d^2}{2}\right) I_0(cd) \quad (30)$$

for $z \in \mathbb{R}^+$, where $c = (\frac{s_b^2 z^2}{\sigma_b^2 z^2 + \sigma_a^2})^{1/2}$, $d = (\frac{s_a^2}{\sigma_b^2 z^2 + \sigma_a^2})^{1/2}$, $Q(c,d)$ is the first order Marcum Q-function, and $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind. Thus, we can equate (30) with ε and solve for $r_{DL_m,i,p}^{(t,k)}$.

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