# Power-efficient Base Station Operation through User QoS-aware Adaptive RF Chain Switching Technique

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*Abstract*— **In this paper, we develop a user Quality of Service (QoS) aware adaptive Radio Frequency (RF) chain switching technique that dynamically adapts the number of active RF chains to minimize the total power consumption of the base station (BS). Specifically, we first formulate an optimization problem to minimize the total power consumption under the throughput and Block Error Rate (BLER) requirements of the users of the BS. Due to the prohibitive complexity of exhaustive algorithm achieving an optimal solution, we propose a practically implementable heuristic algorithm, which jointly optimizes the number of active RF chains, frequency and time resources. Simulation results demonstrate that the proposed algorithm can achieve significant savings in total power consumption of the BSs compared to the conventional static All-On scheme wherein the activity of RF chains is not adapted.**

## I. INTRODUCTION

The explosive growth of the mobile data traffic has significantly increased the power consumption of cellular networks. Increasing the energy-efficiency of base stations (BSs) which reportedly consume about 60-80% [1] of the total power consumption, becomes a critical requirement to reduce growing operating cost for mobile operators, as well as in accordance with the trending global desire to reduce energy consumption and increase sustainability. Amongst many components of the BS, the power amplifier (PA) in RF chain consumes about 65% [2] of the total power consumption in the BS. Further, multi-input multi-output (MIMO) BS providing high data rates and enhanced coverage uses multiple RF chains and thus increase the contribution of the RF chain power consumption. Consequently, in order to reduce BS power consumption, it is vital to develop techniques that can lower RF chain power consumption.

The power consumption of RF chain is determined by BS resources, namely (a) the number of active RF chains, (b) transmit power of PAs, (c) transmission bandwidth and (d) duration of transmission. Finding an optimal combination to minimize the RF chain power consumption is challenging because the above mentioned factors cannot be selected independently of each other. Moreover, the selection of a particular combination of the BS resources for a user would affect the selection for the other users associated with the same BS competing for the shared resources. Lastly, but not the least, this optimization should be done in such a manner that the QoS requirements of all the users having different channel conditions are satisfied.

In this paper, we consider the widely adopted MIMO – orthogonal frequency division multiple access (OFDMA) systems and tackle the above mentioned challenges by developing a RF chain switching technique. The proposed technique jointly adapts the MIMO mode together with the number of active RF chains, frequency and time resources utilized to minimize the total BS power consumption while maintaining the QoS of users and ensuring BS resource utilization does not exceed a certain threshold.

### *A. Related Work*

Various techniques have been proposed to reduce the power consumption of BS and can be broadly grouped in to following three categories: (i) BS on/off, cell zooming by transmit power and/or user association adaptation applied to multi cell – multi user scenario, (ii) adaptation of number of active RF chains and/or selection and switching between PAs of different output power capabilities for each RF chain applied to single cell – multi user scenario and (iii) MIMO parameter adaptation applied to single cell – single user scenario.

Dynamic BS switching on/off and cell zooming techniques proposed in [3-5] can minimize the BS power consumption by completely shutting down some under-utilized BSs. Even though such techniques can obtain huge energy savings, the mobile operators may be reluctant to turn off their BSs due to many practical concerns, e.g., potential coverage holes and degradation in uplink performance.

The time slot based multi cell coordinated napping strategy called CoNap [6] puts BSs in idle mode by switching off all the RF chains in the designated time slot and switches them back to active mode. Though CoNap switches off the RF chains, it does not dynamically adapt the number of active RF chains. Techniques proposed in [7] and [8] adapt the number of active RF chains and frequency resources allocated to each user with [7] additionally adapting BS transmit power and [8] adapting time resources while satisfying the user throughput requirements.

However, neither approach have considered the impact of adapting number of active RF chains, frequency and time resources on MIMO transmission mode selection and BLER of each user and BS utilization, which is the main focus of this paper. The PA selection and switching (PAS) techniques proposed in [9] can reduce the RF chain power consumption by selecting the most efficient PA(s) that satisfies the users' throughput at the required output power level. However, unlike the PAS technique requiring multiple PAs of different output power capabilities for each RF chain resulting in increased system complexity, our technique focuses on reducing the power consumption of

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RF chains with single PA by adapting the number of time slots and frequency blocks over which the PA is active.

In [10], the authors investigated an optimal set of MIMO parameters to minimize overall link energy. While the technique determines the mode for each user by taking in to consideration both throughput and BLER requirements, it only can be applied to a single user and not to a multi user scenario as it does not take in to account the effect of MIMO parameter adaptation on BS utilization.

To the best of our knowledge, this is the first work that considers the joint adaptation of number of active RF chains, frequency and time resources while satisfying the QoS requirements of multiple users and also ensuring the BS utilization constraint is satisfied. The rest of the paper is organized as follows. Section II formally describes the system model and presents the formulation of the optimization problem. In Section III, we propose a solution to the optimization problem based on a heuristic algorithm. In Section IV, we provide simulation results under a practical configuration. Finally, we conclude the paper in Section V.

## II. System Model and Problem Formulation

In this section, we will first present the system model comprising of network, channel, user QoS and BS power consumption models. Then, we formulate the optimization problem to minimize the total BS power consumption with the constraints of user QoS and BS utilization.

### A. Network, Channel and User QoS Model

Consider the downlink communication in MIMO – OFDMA cellular network with set of BSs $B$. Without loss of generality, we will consider one BS, $b \epsilon B$ and $I$ associated users. The overall bandwidth $BW$ is divided in to $J$ equally sized frequency blocks and the transmission duration, a frame is divided in to $T$ equally spaced time slots. The maximum number of RF chains that can be active at the BS and each user device are $S$ and $R$, respectively. Given $S$ and $R$, the set of all possible transmission modes $\boldsymbol{M} \triangleq \{(s_i, r_i, d_i) \mid s_i = 1,2,..,S,\ r_i = 1,2,..,R,\ d_i = 1,2,..,\min(s_i, r_i)\}$, where $s_i$ is the number of BS RF chains assigned to the $i^{th}$ user, $r_i$ is the number of RF chains used by the $i^{th}$ user and $d_i$ is the number of independent data streams transmitted to the $i^{th}$ user. We assume single-input single-output (SISO) and Single User-MIMO (SU-MIMO) including spatial multiplexing (SM) and spatial diversity (SD) modes for transmission.

In modeling channel environment between BS $b$ and $i^{th}$ user on subcarrier $j$, frequency selective and spatially uncorrelated block fading channels with $\boldsymbol{H} = [\boldsymbol{h}_{ij}]_{I\mathrm{x}J}$ is assumed. Elements in $\boldsymbol{H}$ are assumed to be independent and identically distributed random variables with zero mean and variance $\mu_i$. The noise at each user's receiver is assumed to be additive white Gaussian with zero mean and variance $\sigma^2$. We further assume that the instantaneous channel state information (CSI) including channel quality information (CQI) for all the $J$ frequency blocks and spatial channels, and Rank Indicator (RI) from the user is available at the BS.

The throughput $TP_i$ from the BS to the $i^{th}$ user depends on the channel experienced by the user, the transmit power $P_{Tx}$ of the BS, the number of time slots assigned for transmission $T_i$, the number of frequency blocks assigned $J_i$ and the mode $m_i \in \boldsymbol{M}$ chosen for transmission. In this work, we assume mode selection is done once every frame and also that $m_i$ does not change within time slots of a frame. Assuming that the channel remains constant in a frame, the throughput $TP_i$ is given as [7].

$$TP_i(m_i, J_i, T_i) = BW \cdot d_i \frac{T_i}{T}\frac{J_i}{J} \cdot \log_2\left(1 + \frac{\mu_i s_i r_i P_{Tx}}{J d_i^2 \sigma_i^2}\right) \quad (1)$$

The $BLER_i$ achieved for the $i^{th}$ user depends on the transmit power $P_{Tx}$, channel experienced by the user $\boldsymbol{H_i}$, and the mode selected $m_i$.

$$BLER_i = f(P_{Tx}, \boldsymbol{H}_i, m_i) \quad (2)$$

where $\boldsymbol{H_i} = [\boldsymbol{h}_{ij}]_{1\mathrm{x}J}$ represents the spatial channel matrix. Throughout the paper, the QoS of user will refer to the user's throughput and BLER requirements.

### B. Base Station Power Consumption Model

The BS power consumption model requires to capture the power consumption of various components, the effect of PA state and state transition, for instance from active state to off state, the time and frequency resource utilization in different PA states and RF chain analog circuitry state and state transition. We will next model and discuss in detail the power consumption due to various BS components, state of PA, time and frequency utilization in different PA states and analog circuitry states.

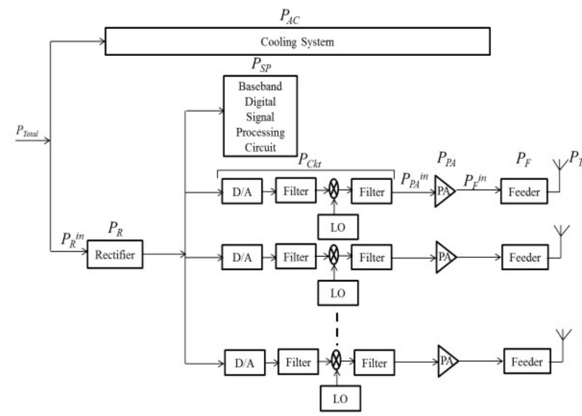


Fig. 1. Base Station Components and Power Flow

Fig. 1 shows the four main components of BS namely, rectifier, baseband digital signal processing circuitry, RF chain and cooling system and the power consumed by each component. It should be noted that Fig. 1 shows the power flow and not the signal flow. The rectifier transforms the signal from AC to DC. The rectifier power consumption $P_R$ is a function of the rectifier input power $P_R^{in}$ and efficiency $\eta_R$, i.e., $P_R = P_R^{in} \cdot (1 - \eta_R)$ [11]. The baseband digital signal processing circuit performs channel coding and modulation, MIMO encoding and OFDM modulation. The baseband digital signal processing power consumption $P_{SP}$ is assumed to be constant [11]. The RF chain consists of the digital to analog converter (D/A), filter, mixer [12], PA and feeder as shown in Fig. 1. The digital signals output by the baseband digital signal processing circuit are converted to analog signals by the D/A, filtered and up converted to a higher frequency band. We will henceforth refer to the D/A, filter and mixer as RF chain analog circuitry, the power consumption of which denoted by $P_{Ckt}$ is given by

$$P_{Ckt} = C_{Ckt} \cdot F_{Slot} \tag{3}$$

where $C_{Ckt}$ is a constant [12] and $F_{Slot}$ depends on the duration of active state of the PA as will be explained later in this section. The PA amplifies the signal output by the analog circuitry and the power consumption $P_{PA}$ is a function of the PA input power $P_{PA}^{in}$ and PA efficiency $\eta_{PA}$ given by $P_{PA} = P_{PA}^{in} \cdot (1 - \eta_{PA})$ [11]. The feeder feeds the signals amplified by the PA to the physical antenna. The feeder power consumption is given by $P_F = P_F^{in} \cdot (1 - \eta_F)$ where, $P_F^{in}$ is the feeder input power and $\eta_F$ is the feeder efficiency. The BS transmit power $P_{Tx}$ is equal to the power output of the feeder, i.e., $P_F = P_F^{in} \cdot \eta_F$. The cooling system maintains the components of the BS within the specified operating temperature limits and its power consumption $P_{AC}$ given by $P_{AC} = (P_R^{in} - P_{Tx})/3$ is a function of the difference in rectifier input power and $P_{Tx}$ [11].

As PA is the major contributor to BS power, we will delve deeper in to the two states of operation of the PA and their impact on PA power consumption. PA can be either in the active state where it is transmitting or in the off state. The corresponding state power consumption is $P^{Active}$ and $P^{Off}$ respectively and the power consumed during state transition is $P^{SW}$. Of the two states, the active state consumes most power. In order to determine the total power consumed by the PA in a frame, we will define utilization of PA in the time domain as $\rho$ and in the frequency domain as $\psi$. We will first define time utilization in each of the state as fraction of frame duration spent in that particular state. If $T^{Active}$ and $T^{Off}$ are number of time slots in which the PA is in active and off state respectively, then corresponding utilization is defined as

$$\rho^{Active} = T^{Active}/T \tag{4}$$

$$\rho^{Off} = T^{Off}/T \tag{5}$$

We assume that the PA switching time $T^{SW}$ is much lower than the duration of time slot and define switching utilization as

$$\rho^{SW} = T^{SW}/T \tag{6}$$

The total time utilization $\rho$ is defined as

$$\rho = \rho^{Active} + \rho^{Off} + \rho^{SW} \tag{7}$$

As the entire BW can be used for transmission, frequency utilization $\psi$ is defined as the fraction of $BW$ or $J$ utilized.

$$\psi_t = \begin{Bmatrix} \frac{\sum_{i=1}^{I} J_{t,i}}{J} & when\ PA\ is\ Active \\ 0 & when\ PA\ is\ Off \end{Bmatrix} \tag{8}$$

where $\sum_{i=1}^{I} J_{t,i}$ is the total number of frequency blocks assigned to $I$ users in time slot $t$. Having defined the PA time and frequency utilization in different states, the PA power consumption [11], [13] can be written as

$$P_{PA} = \left[\frac{(1-\eta_{PA})P^{Active}}{T}\sum_{t=1}^{T^{Active}} \psi_t + \rho^{Off} P^{Off} + \rho^{SW} P^{SW}\right] \tag{9}$$

The RF chain analog circuitry is assumed to operate in two states, on and off with power consumption $P_{Ckt}^{On}$ and $P_{Ckt}^{Off}$ respectively. When the PA is active, the analog circuitry is on and when PA is switched off, analog circuitry is switched off. We assume negligible $P_{Ckt}^{Off}$, switching power and switching time for analog circuitry. Therefore, in (3), $C_{Ckt} = P_{Ckt}^{On}$ and $F_{Slot} = T^{Active}/T$. As the total RF chain power consumption $P_{RF}$ is the sum of the power consumed by the PA and analog circuitry, it is given by

$$P_{RF} = P_{PA} + P_{Ckt} \tag{10}$$

Note that the power consumption of analog circuitry is independent of frequency utilization and is present when the RF chain is turned on, i.e., active.

The total rectifier input power is given by

$$P_R^{in} = \frac{P_{SP}}{\eta_R} + \frac{1}{\eta_R}\sum_{s=1}^{S} P_{RF,s} \tag{11}$$

The total BS power consumption can be written as

$$P_{Total} = P_R^{in} + P_{AC} \tag{12}$$

From (1) and (2), it is evident that the utilization of BS resources, including the number of active RF chains, frequency blocks and time slots depends on the mode chosen. User mode selection depends on QoS requirements and availability of BS resources. We can infer from (3) – (12) that BS power consumption depends on aggregate BS resource utilization which in turn is determined by mode selection for all users. Therefore, minimization of total BS power consumption involves tradeoff between utilization of number of RF chains, frequency and time resources and mode selection while satisfying the QoS of users and maintaining the BS utilization below a certain threshold.

### C. Problem Formulation

We now formulate a general optimization problem to minimize the total BS power consumption while satisfying the QoS requirements of all users and maintaining the BS utilization below the utilization upper bound in both time and frequency domains.

$$\begin{aligned} \text{min} \quad & P_{Total} \\ \text{subject to} \quad & TP_i \geq \gamma_i, i = 1,2,..,I \\ & BLER_i \leq BLER_i^{TH}, i = 1,2,..,I \\ & 0 \leq s \leq S \\ & \rho_s \leq 1, s = 1,2,..,S \\ & \psi_{t,s} \leq 1, t = 1,2,..,T, s = 1,2,..,S \end{aligned} \tag{13}$$

where $\gamma_i$ is the rate required by the $i^{th}$ user, $BLER_i^{TH}$ is the upper bound on BLER for the $i^{th}$ user. We will optimize $s$, $\rho$ and $\psi$ to minimize $P_{Total}$ while satisfying the constraints. Throughout this paper, this optimization will be carried out with the frame as reference.

## III. Min-Cost Algorithm

In this section, we will present the Min–Cost heuristic algorithm developed to minimize $P_{Total}$ while satisfying QoS and BS utilization constraints.

We assume that $I$ users are scheduled based on the scheduling policy in a given frame. In the frame, the BS can allocate up to $S$ RF chains, $T$ time slots and $J.T$ frequency blocks to the users. The resource allocation and assignment will determine the mode, achievable BLER and throughput for each user and also the BS utilization. However, given $\gamma_i$ and CSI of each user and BS utilization, there may exist multiple modes that satisfy the constraints. The solution to (13) is an optimum combination of modes selected for $I$ users. So the complexity of exhaustive search is exponential to the total number of users, i.e., $O(|\boldsymbol{M}|^I)$, where $|\boldsymbol{M}|$ denotes the cardinality of the set of all possible modes $\boldsymbol{M}$.

In order to reduce the complexity, we propose to select the mode that minimizes RF chain power consumption for each user. The modes selected for all the users determine the BS utilization. For each user $i$ after mode selection, let $T_i$, $a_{t,i}$ and $\psi_{t,s,i}$ denote the number of active time slots, the number of active RF chains in time slot $t \in T$ and frequency utilization of RF chain $s \in S$ in time slot $t$ respectively. The proposed approach is based on the following observations. (i) The number of active RF chains in $t \in T$ is $a_t = \max_{\{i=1,2,..,I\}} a_{\{t,i\}}$, (ii) the frequency utilization of each RF chain $s \in S$ in $t \in T$ is $\psi_{t,s} = \sum_{i=1}^{I} \psi_{t,s,i}$ and (iii) the number of active time slots for each RF chain $s \in S$ is $T_s^{Active} = \max_{\{t=1,2,..,T\}}\{t|\,\psi_{\{t,s\}} > 0\}$. From these observations, it can be inferred that the number of active RF chains, frequency utilization and active state time utilization of each RF chain can be minimized if each is minimized for every user. However, minimizing each for every user in isolation will lead to an increase in the others because (a) decreasing $a_t$ may increase $\psi_{t,s}$ and $T_s^{Active}$, (b) decreasing $\psi_{t,s}$ may increase $a_t$, the total RF chain analog circuitry power (second term in (11)) and $T_s^{Active}$ and (c) decreasing $T_s^{Active}$ may increase $a_t$, the total RF chain analog circuitry power and $\psi_{t,s}$. Therefore joint adaptation of the above factors is required to minimize RF chain power consumption and thereby total BS power consumption. The Min–Cost algorithm based on joint adaptation of the BS resources to minimize $P_{Total}$ is shown in Fig. 2 and explained in detail below.

For each user $i$, depending on inputs and scheduling policy, the scheduler outputs mode $m_i$, active time slots $T_i$ and frequency blocks $J_i$. In this work, we extend this scheduler output to include the time and frequency resources for all modes $m \in \boldsymbol{M}$. Step 3 in Fig. 2 executed for all modes generates the extended scheduler output as explained in detail in Section IV with reference to a representative scheduler. The steps 4-7 of Min–Cost algorithm determine the set of feasible modes $\boldsymbol{M_i^{FS}} \subseteq \boldsymbol{M}$ that satisfies the constraints for each user. Given $\boldsymbol{M_i^{FS}}$, we will now discuss the cost function which is the basis of Min-Cost algorithm. Consider a feasible mode $m \in \boldsymbol{M_i^{FS}}$ that requires $a_{m,i}$ number of active RF chains, $T_{m,i}$ active time slots, $J_{m,t,s,i}$ frequency blocks for RF chain $s \in a_{m,i}$ in

**Input:** $\boldsymbol{I}$, $\{\gamma_i|i = 1,2,..,I\}$, $\{BLER_i^{TH}|i = 1,2,..,I\}$, $\{RI_i|i = 1,2,..,I\}$, $\{(CQI_{1,l,i}, CQI_{2,l,i},..,CQI_{J,l,i})|l = 1,2,..,RI_i, i = 1,2,..,I\}$, $\{\boldsymbol{H_i}|i = 1,2,..,I\}, S, R, J, T$

**Output:** $\{a_t|\, t = 1,2,..,T\}$, $\rho_s, s = 1,2,..,S$ $\{\psi_{t,s}|t = 1,2,..,T, s = 1,2,..,S\}$

**1: For** all users $i = 1,2,..,I$
**2:** **For** all modes $m \in \boldsymbol{M}$
**3:** Scheduler outputs $(m, J_{m,i}, T_{m,i})$ where, $J_{m,i} = \sum_{t=1}^{T_{m,i}} J_{m,t,i}$
**4:** Determine $TP_i(m, J_{m,i}, T_{m,i})$ using (1)
**5:** Determine $BLER_i(P_{Tx}, \boldsymbol{H_i}, m)$ using Look Up Table (LUT) explained in Section IV
**6:** **If** $TP_i(m, J_{m,i}, T_{m,i}) \geq \gamma_i$ and $BLER_i(P_{Tx}, \boldsymbol{H_i}, m) \leq BLER_i^{TH}$ and $T_{m,i} \leq T$ and $J_{m,t,i} \leq 1$
**7:** **Then** update feasible mode set $\boldsymbol{M_i^{FS}} = \boldsymbol{M_i^{FS}} \cup m$
**8:** Compute $C_i(m)$ using (14)
**9:** **End** all modes
**10:** Find mode that results in minimum cost $m_i^* = argmin_{m \in \boldsymbol{M_i^{FS}}} C_i(m)$
**11: End** all users

**12: For** all time slots $t = 1,2,..,T$
**13:** Determine number of active RF chains, $a_t = \max_{\{i=1,2,..,I\}} a_{\{t,i\}}$
**14:** Determine the number of RF chains in the off state $o_t = S - a_t$
**15:** Determine frequency utilization $\psi_{t,s} = \sum_{i=1}^{I} \psi_{t,s,i}, s = 1,2,..,a_t$ $\psi_{t,s} = 0, s = 1,2,..,o_t$
**16: End** all time slots

**17: For** all RF chains $s = 1,2,..,S$
**18:** Determine number of active time slots $T_s^{Active} = \max_{\{t=1,2,..,T\}}\{t|\,\psi_{\{t,s\}} > 0\}$
**19:** Determine number of off time slots $T_s^{Off} = T - T_s^{Active} - T_s^{SW}$
**20:** Compute $\rho_s$ using (7)
**21: End** all RF chains

Fig. 2. Min-Cost Algorithm

time slot $t \in T_{m,i}$. As the frequency utilization for all active RF chains in a given slot $t$ is the same, we drop the subscript $s$ from $J_{m,t,s,i}$. The RF chain power consumption is the cost incurred when mode $m$ is selected for user $i$. The cost function $C_i(m)$ is given by

$$C_i(m) = a_{m,i} \cdot \left[\frac{P_{Active}}{T} \cdot \sum_{t=1}^{T_{m,i}} \psi_{m,t,i} + \frac{T_{m,i}}{T} \cdot P_{Ckt}^{On}\right] \quad (14)$$

The cost function is calculated for every mode $m \in \boldsymbol{M_i^{FS}}$ in Step 8 and the mode $m_i^*$ that results in minimum cost is chosen in Step 10. If more than one mode achieves the same minimum cost then the mode that gives the highest throughput is retained as $m_i^*$. The output of the algorithm is the number of active RF chains $a_t$ in each time slot $t \in T$, the frequency utilization $\psi_{t,s}$ of each RF chain $s \in S$ in each time slot $t \in T$ and time utilization $\rho_s$ of each RF chain $s \in S$ as determined in steps 12-21 in Fig. 2.

As can be seen from steps 2-9, the computational complexity of Min-Cost algorithm to determine the combination of modes is polynomial, i.e., $O(I \cdot |\boldsymbol{M}|)$ as against the exponential complexity of exhaustive search.

## IV. Simulation Results

In this section, we evaluate the performance of the proposed Min–Cost algorithm through simulations. We first describe the framework developed and then provide the results obtained.

### *A. Simulation Framework*

In our simulation, we assume users are uniformly distributed in the cell of a BS. The traffic load is assumed to be spatially heterogeneous with user's required rate $\gamma \propto (max(d) - d)^2$ , where $d$ is the distance between the user and BS. The simulation parameters are summarized in Table I. We adopted the parameters for power consumption from [7], [8] and [11]. Other parameters for the simulations follow the suggestions in the Long Term Evolution (LTE) specifications [14].

We will now discuss the extended scheduler output in step 3 of Fig. 2. The iterative frequency domain scheduler proposed in [15] is extended to allocate and assign frequency blocks and time slots to different modes in a frame for all $I$ users. In every iteration, the scheduler assigns that frequency block on which the user experiences highest CQI and the iteration is complete when all the users

TABLE I. Simulation Parameters

| | |
|---|---|
| Rectifier efficiency $\eta_R$ | 92% |
| Signal Processing Power $P_{SP}$ | 100W |
| RF chain analog circuitry on power $P_{Ckt}^{On}$ | 5W |
| PA efficiency $\eta_{PA}$ | 20% |
| PA active and off power ($P^{Active}, P^{Off}$) | (200W, 3.5W) |
| PA idle power $P^{Idle}$ | 100W |
| PA switching power $P^{SW}$ | 100W |
| PA switching time $T^{SW}$ | 35us |
| Feeder efficiency $\eta_F$ | 50% |
| Maximum transmit power $P_{Tx}^{Max}$ | 40W |
| Bandwidth $BW$ | 5MHz |
| Number of time slots $T$ | 10 |
| Duration of frame | 10ms |
| Number of frequency blocks $J$ | 25 |
| Number of RF chains at BS $S$ | 4 |
| Number of RF chains at user device $R$ | 4 |
| Set of modes $\boldsymbol{M}$ | 1x1 (SISO),<br>2x2 (SM or SD),<br>4x2 (SM-SD),<br>4x4 (SM),<br>4x1 (SD) |
| $\lvert\boldsymbol{M}\rvert$ | 6 |
| Number of users $I$ | 25 |
| $BLER^{TH}$ for all $I$ users | 0.1 |
| Simulation time | 48 hours |

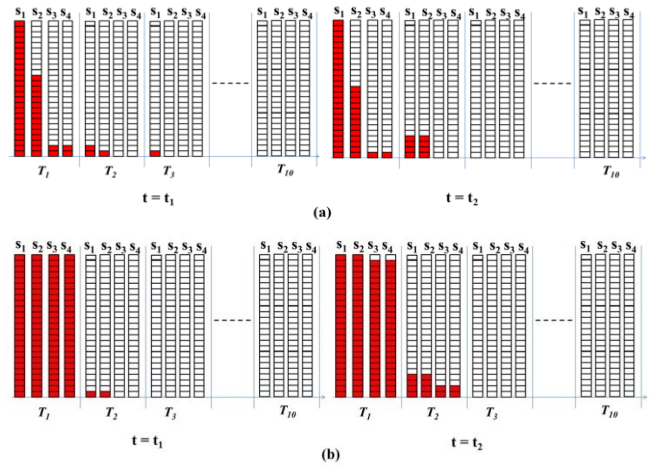

Fig. 3. RF chain, frequency and time utilization in a frame in two sampling instants for (a) Min-Cost and (b) All-On

have been assigned one frequency block. At the end of $k^{th}$ iteration, the $SNR_i$ for $i^{th}$ user is updated as the minimum of the effective SNR (ESNR) values of the $k$ frequency blocks $J_k$ assigned. The throughput of each mode $m \in \boldsymbol{M}$ is calculated using (1) and if user rate is satisfied, the number of frequency blocks required for mode $m$ is $J_{m,i} = J_k$ and the number of active slots required for mode $m$ is $T_{m,i} = \max_{\{t=1,2,..,T\}}\{t|\,\psi_{\{m,t,i\}} > 0\}$. In this manner, the number of frequency blocks $J_{m,i}$ and active time slots $T_{m,i}$ determined for each mode forms the output of step 3 in the Min–Cost algorithm.

The $BLER_i$ in step 5 of Min–Cost algorithm is determined as follows. All the users in the cell report CSI measurement [14] every frame. The Look Up Table (LUT) in [16] is extended to include 4x1 and 4x4 modes and specifies the lower SNR bound $SNR^{TH}$ required for different modes to result in BLER $\leq$ 0.1 when different CQI values are used. For the SISO mode, we use the $SNR^{TH}$ determined without retransmission to map the CQI to the corresponding SNR value. The SNR of $i^{th}$ user $SNR_i$ is compared to $SNR^{TH}$ for all permissible modes (depending on RI) in LUT. If the condition $SNR_i \geq SNR_m^{TH}$ (SNR threshold for mode $m$) is satisfied, then BLER for mode $m$ is set to $BLER_{m,i} = BLER_i^{TH}$ and to an arbitrary value $> BLER_i^{TH}$ otherwise. The remaining steps 6-21 of the Min–Cost algorithm are executed as shown in Fig. 2.

### *B. Simulation Results*

In order to evaluate the performance of the proposed algorithm in a practical setting, we adopt a sample traffic trace given in [1]. The trace, originally obtained from an anonymous cellular operator, captures the variation in BS utilization with temporal granularity of 1 minute across 48 hours in a metropolitan area. For performance comparison, we consider the All-On scheme as a baseline, which turns on all BS RF chains in active time slots and turns off in off slots. For All-On, the RF chains that are on but not used for transmission are considered to be in idle state and $P^{Idle} = 100W$ [11] is used as the corresponding power consumption. The performance of the All-On scheme is

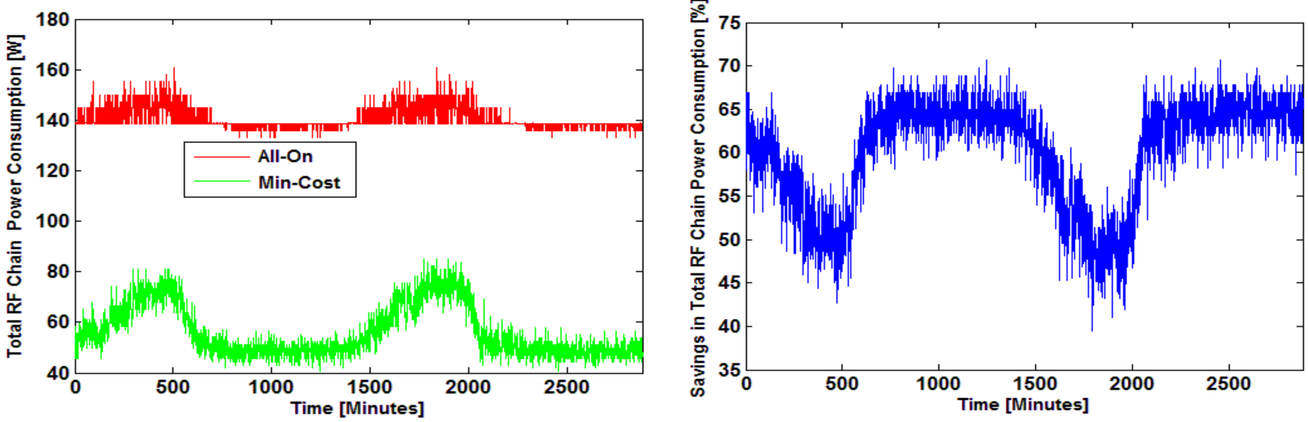


Fig. 4. (a) Total RF chain power consumption (b) Savings in total RF chain power consumption of Min-Cost compared to All-On

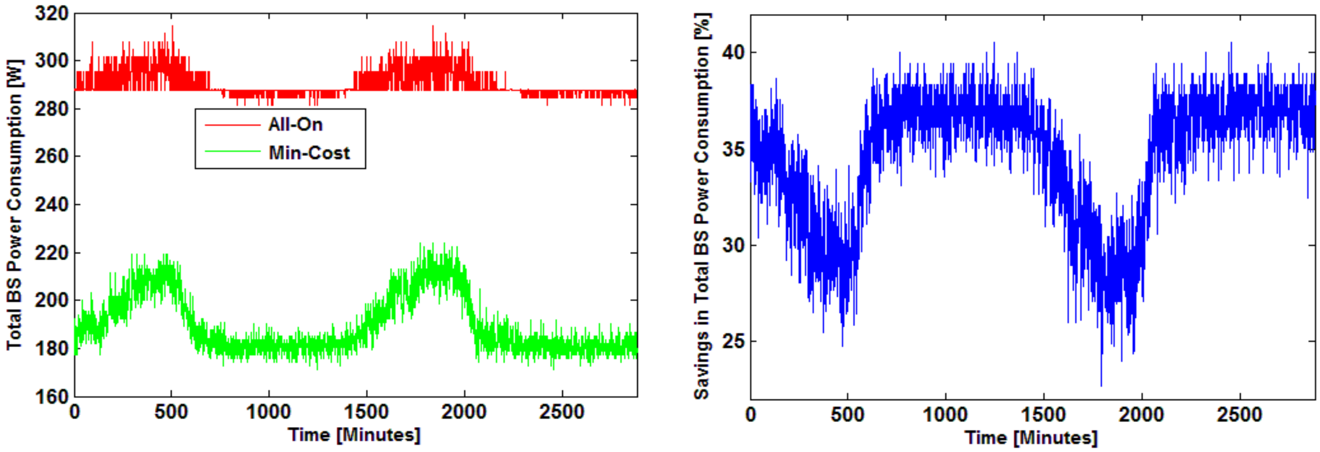


Fig. 5. (a) Total BS power consumption (b) Savings in total BS power consumption of Min-Cost compared to All-On

evaluated using the same framework except that the mode selection criterion is different. For the All-On scheme, the maximum throughput mode is chosen for all users.

To illustrate the adaptation of BS resource utilization, let us consider the BS resource utilization for Min–Cost and All–On schemes in two representative simulation steps at $t = t_1$ and $t = t_2$ as shown in Figs. 3(a) and 3(b). Note that the load and channel is assumed to be constant within the simulation step. In Fig. 3, the time slots are denoted by $T_1, T_2, .., T_{10}$, the RF chains are denoted by $s_1, s_2, .., s_4$ and the frequency blocks corresponding to each RF chain are represented by black outlined boxes. The boxes shown in red indicate that the particular $j^{th}$ frequency block is utilized for transmission. For the purpose of discussion, we will represent the frequency utilization of all RF chains in each active time slot as an $S$ tuple. In a single frame in $t = t_1$, for Min–Cost, the number of active time slots is 3 and in $T_1, T_2$, and $T_3$, the number of active RF chains is 4, 2, and 1 and the corresponding frequency utilization is (25,15,2,2), (2,1,0,0) and (1,0,0,0). As noted in Fig. 2, Min-Cost dynamically adapts the number of RF chains in each time slot. For example, it will switch off two RF chains in $T_2$, another RF chain in $T_3$ and the last remaining RF chain in $T_4$. The resulting total BS power consumption is 210W. On the other hand, for All – On in Fig. 3(b), the number of active time slots is 2 and in $T_1$ and $T_2$, the number of active RF chains is 4 and 2 and corresponding frequency utilization is (25,25,25,25) and (1,1,0,0). Though Min-Cost requires one additional active slot, the frequency utilization is higher for all active RF chains in case of All-On resulting in 31% increase in $P_{Total}$. At $t = t_2$, the number of active time slots for both Min-Cost and All-On is same, but higher number of active RF chains and frequency utilization for All–On results in about 30% increase in $P_{Total}$. Also, Fig. 3(a) illustrates that Min-Cost adapts the number of active RF chains, frequency and time resource across frames whereas Fig. 3(b) shows that All-On tends to utilize all the RF chains to the maximum.

Next, we will discuss the effect of adaptive RF switching on total RF chain power consumption and total BS power consumption. Fig. 4(a) shows the total RF chain power consumption given by (10) for Min–Cost and All–On. All–On consumes higher power than Min-Cost because regardless of load, all the RF chains are on in the active time slots. This increases total RF chain power consumption due to (a) higher frequency utilization for each active RF chain and/or (b) higher RF chain analog circuitry power consumption as all RF chains are either in active or idle state. Joint minimization of number of active RF chains, frequency and time utilization reduces the total RF chain power consumption for Min–Cost. Fig. 4(b) shows the reduction in total RF chain power consumption of Min–Cost compared to All–On. Up to 70% savings in total RF chain power consumption can be achieved due to Min-Cost algorithm. Fig. 5(a) shows the total BS power consumption given by (12) for Min–Cost and All–On. The variation in total BS power consumption shows similar trend as that of total RF chain power consumption. From Fig. 5(b), it is evident that significant savings of up to 40% in BS total power consumption can be achieved by the proposed Min–Cost algorithm.

## V. CONCLUSION

In this paper we proposed a novel user QoS-aware adaptive RF switching technique that jointly adapts the number of active RF chains, frequency and time resources to minimize the total BS power consumption. Through simulations, we demonstrated that the proposed technique can produce significant savings in RF chain and total BS power consumption while satisfying the user's QoS requirements and maintaining BS utilization below the threshold. While our current RF chain power consumption model includes both the fixed power component (dependent on RF chain analog circuitry) and variable power component (dependent on number of frequency blocks utilized), we plan to extend the variable power component to further account for the nonlinear operation of PA when transmit power varies [17]. Subsequently, we aim to include transmit power adaptation as part of the proposed technique and integrate the same in the DCR framework [3] in order to further reduce the BS power consumption.

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