

# Energy Aware Buffer Aided Cooperative Relay Selection

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**Abstract**—In this paper we evaluate an energy aware relay selection mechanism which exploits channel state information and the availability of buffers at relays to perform flexible relaying based on a back-pressure driven optimization model. This model ensured maximization of the cell throughput while maintaining the stability of backlog queues. Performance evaluation is conducted using a System Level Simulator which is fully compliant with IEEE 802.16m and supports various relaying scenarios. The Below Roof Top (BRT) relaying scenario is considered in this work. A holistic and flexible energy framework is implemented to capture the energy consumption of the cellular network nodes. The model maps the RF output power radiated at the antenna elements of each node including relays on the network to the total supply power of the node equipment. Two derivatives of the proposed mechanisms, half duplex and full duplex are proposed and evaluated. Results of the two derivatives on BRT relaying scenario revealed noticeable increases for both cell throughput and system energy efficiency of the cell-edge users compared to conventional relaying protocols and non cooperative scheme.

**Keywords** – relay, two hop network, energy efficiency, energy aware, relay selection, buffer-aided, throughput, WiMAX, and LTE.

## I. INTRODUCTION

As a technology enabler, relaying has re-emerged over the past decade and has been actively studied and considered in the standardization process of state-of-the-art mobile broadband communication systems such as 4G LTE-Advanced and IEEE 802.16m [1]. This is due not only to relays ability to provide coverage extension but also for their capability to alleviate fading in wireless channels by introducing spatial diversity and for their potentiality to improve overall system energy efficiency for mobile networks [1]. Energy efficiency has swiftly shifted from the state of low priority to a centre of attention within the telecommunication community. The increased network running costs from an operators perspective, government legislation and energy targets, added to an unprecedented awareness in society on the dramatic impact of excessive energy consumption on global warming, are key drivers for improving energy efficiency in mobile network operations [2]. In this work, we primarily study energy aware relaying techniques for mobile wireless networks. We exploit their spatial diversity and storage capabilities to maximize

users throughput and enhance the system energy efficiency by optimizing the relay selection procedure. Relay selection techniques are typically relatively undemanding to implement and can attain the same diversity order compared to more complex schemes employing space time block coding [3] or requiring orthogonal channels [4].

### A. Related Work

The relay selection mechanisms proposed in [5] and [6] perform relaying and forwarding procedures using the same selected relay by receiving data from the source in one time slot and forwarding it in the subsequent slot and do not take advantage of buffers at relays. The most common scheme on this direction is a relay selection algorithm based on a max?min fairness criterion [5]. In this paper, we adopt a similar technique to the latter for the sake of performance benchmarking. In the other hand, the relay selection techniques such as max – max [7] and adaptive link selection algorithm [8] give relays the freedom to decide on which time slot to receive and on which time slot to transmit packets. This capability requires the relays to have embedded buffers which enable them not to transmit data if the channel condition is poor and hold until better access channel conditions occur. However, these buffer aided techniques may suffer from either severe data delivery delays and/or backlog queue stability issues such as overflow and underflow incidents [8].

The seminal work in [9] established a frame work for indicating throughput optimal scheduling in radio networks by introducing the back-pressure algorithm that exploits buffering and queuing backlogs as system state information to derive an optimal scheduling policy. Berry et al. in [10] and [11] have studied cooperative communication models that incorporate stochastic traffic arrivals for multiple sessions as well as the related queuing dynamics in all network nodes. These works employ the Decode-and Forward (DF) relaying technique, in which all cooperating nodes must decode a packet before forwarding it. A two-hop diamond network topology is considered for evaluation purposes, where multiple relays act as intermediary nodes for forwarding the traffic for a particular source-destination pair, and a half-duplex communication constraint is also imposed. The goal of this work is to propose a throughput

and energy consumption optimal policy that stabilizes the network for any arrival rate in its stability region.

The work of Berry does not consider a generic optimization framework as in [9], [12], [13] and [14] rather than focusing solely on maximizing the throughput of a wireless cooperative network. In our work, we adopted the back-pressure algorithm in order to extend Berrys work and to establish a framework that will be used for improving of a cooperative networks performance for a certain power objective while also attaining a performance-delay trade-off.

## B. Our Contributions

In this paper we extend our previous work carried out on relay selection, for Wi-Fi based network [15], [16] and for the IEEE 802.16m Above Roof-Top (ART) system [17], in order to support an energy aware selection for the Below Roof-Top (BRT) relaying scenario. The proposed mechanism exploits transmission queue lengths and channel quality using back-pressure algorithm in order to maximize the energy efficiency and ensure data queue stability at relays. We derive two implementation derivations of the relay selection algorithm and evaluate their performance in an IEEE 802.16m System Level Simulator (SLS) not only in terms of throughput but from an energy efficiency perspective as well. In order to quantify the energy efficiency of the wireless network, the power consumption of the entire system is captured using a well defined holistic framework.

## II. SYSTEM MODEL

We consider a two-hop cellular network topology depicted in Fig. 1 on which one source (base station BS), one destination (mobile station MS) and  $r$  relays ( $r = 6$ ) are deployed. We assume  $BS, RS_1, RS_2, \dots, RS_r$  are equipped with buffers with unlimited storage capacity. We denote  $Q_{BS}(t), Q_{RS_1}(t), Q_{RS_2}(t), \dots, Q_{RS_r}(t)$  as the corresponding data queue lengths to be transmitted at each node for a given time slot  $t$ . We assume that the transmission is organized in packets and the channels are constant for the duration of one time slot and vary independently from one time slot to the next. We also assume that packet injection in the network takes place only on the source node BS and all other nodes receive intra-network traffic. Let us define by  $N_{in}^i$  the set of nodes from which node  $i$  receives internal traffic, and  $N_{out}^i$  the set of nodes that receives from node  $i$ . The queue backlog evolves according to the following equation:

$$Q_i(t+1) = [Q_i(t) - \sum_{b \in N_{out}^i} R_{ib}(t)]^+ + A_i(t) + \sum_{a \in N_{in}^i} R_{ai}(t), \quad (1)$$

where  $[\cdot]^+ = \max(\cdot, 0)$  and  $A_i(t)$  are the exogenous arrivals on node  $i$  at time slot  $t$  (as previously mentioned, only the source node BS receives exogenous arrivals in the network). The transmission rate  $R_{ab}(t) = R_{ab}(S_{ab}(t))$  in the link (ab) on slot  $t$  depends on the link channel state condition  $S_{ab}(t)$  and it is determined by the transmission power and the channel condition. We assume that the channel state  $S_{ab}(t)$  is known at the beginning of each time slot  $t$  and remains constant over its duration, but it can be variable throughout time slots.  $\sum_{a \in N_{in}^i} R_{ai}(t)$  refers to the cumulative internal traffic arriving

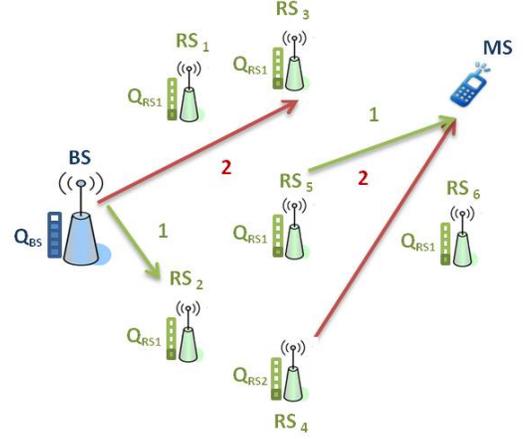


Fig. 1: System model of cellular topology mapped to WiMAX BRT scenario: one source, 6 relays, and one destination.

at node  $i$  at time slot  $t$  and  $\sum_{b \in N_{out}^i} R_{ib}(t)$  is the traffic served from node  $i$  to all other nodes at slot  $t$ .

The relays  $\{RS_1, \dots, RS_r\}$  assist the source node BS whenever channel conditions (or other factors such as queue congestion) do not favour direct source-destination transmission by carrying out traffic through alternative links. In this work relays assistance is considered as long as the Signal to Interference plus Noise Ratio (SINR) of at least one of the access links  $RS_k - MS, k = 1 : r$  is superior to the SINR of the direct link  $BS - MS$ . For relay assisted transmission, we consider two transmission protocols, the half duplex and full duplex scheduling. For half duplex the relay links  $\{BS - RS_k, k = 1 : r\}$  and the access links  $\{RS_k - MS, k = 1 : r\}$  are interference free and impose the constraint that, at any time slot  $t$ , either access links or relay links are activated at a time. In full duplex mixed links  $BS - RS_m$  and  $RS_n - MS, \forall m \neq n$  can operate simultaneously. Note that in full duplex the same relay is not allowed to transmit and receive at the same time slot therefore the pair  $(BS - RS_m, RS_n - MS, m = n)$  is a prohibited combination. The full duplex scheme will ensure transmission of extra packets compared to half duplex but with the cost of introducing interference at the receiving node (either MS or RS) from simultaneously transmitting nodes which could either BS or RS. We also assume that the source node BS has access to Channel Quality Index (CQI) of all links and the BS is responsible for selecting the relays allocated for transmission and reception.

### A. Relay selection rule

Next we describe the proposed buffer aided relay selection mechanism. The proposed relay selection exploits the availability of buffers and CQIs of all links to perform relay selection which maximize the throughput and maintain queue stability at the buffers. The links are activated in pairs to take full advantage of the available data pending for transmission at relays. The scheduling rule is derived from the back-pressure algorithm [9] based on Lyapunov drift [13] in order to optimize the aggregate network congestion reflected by the sum of

squares of queue backlogs:

$$L(\Theta(t)) := \frac{1}{2}\Theta(t)^2 := \frac{1}{2}Q(t)^2, \quad (2)$$

We generalize the optimization problem by including a power consumption minimization component to the throughput maximization framework in similar fashion to our previous work presented in [16], [17]. Therefore, the selected relay pair can be obtained by:

$$(\hat{m}, \hat{n}) = \arg \left( \max_{m,n} \left( (Q_{BS} - Q_{RS_m})R_{BS,RS_m} + Q_{RS_n}R_{RS_n,MS} - V(P_{BS,RS_m} + P_{RS_n,MS}) \right) \right) \quad (3)$$

Where  $(\hat{m}, \hat{n})$  are the indexes of the selected pair  $(BS - RS_{\hat{m}}, RS_{\hat{n}} - MS)$ ,  $P_{a,b}$  is the power consumption estimation of the link  $a-b$  transmission and  $V$  is an adjustable parameter. In case of full duplex the pair  $\hat{m} = \hat{n}$  is a forbidden selection since relay cannot operate as transmitter and receiver at the same time.

### B. Relay Selection Analysis

The adjustable parameter  $V$  introduced to balance between maximizing the throughput and minimizing the power consumption. The following scenario can occur:

a)  $V = 0$ , then power consumption expression is disregarded, and the problem reduces to stabilizing queues and maximizing the throughput. It is indeed the maximum throughput approach with no consideration of power consumption.

b)  $V \gg 0$ , the power consumption expression dominates all other queuing factors in [3]. The problem is reduced to select only power efficient schedules without any consideration of queuing backlogs.

c) for moderate  $V > 0$  this is the intermediary regime where we seek to attain a desired power-throughput performance trade-off. For large values of  $V$  the policy selects more power conservative schedules causing larger queues and larger networking delay.

## III. NETWORK POWER MEASUREMENT FRAMEWORK

A holistic power model that maps the RF output power radiated at the antenna elements ( $P_{out}$ ), to the total supply power of node equipment ( $P_m$ ) as developed based on power framework developed within FP7 EARTH project [18], [19]. Note that the EARTH model is primarily designed based on the 4G LTE system specification [19]. Some changes are required to support the WiMAX system. The changes made are manageable thanks to the two systems similarities and the model flexibility and granularity. The changes are mainly related to relay modeling and will be illustrated in due course.

### A. Flexible Power Modeling

This section attempts to summarize at high-level the flexible model used in this work. The model considers all nodes which are involved in a transmission (BS and RS). Even though the MS power can be modeled using the same framework, to a certain extent, it is omitted on this study for simplicity reasons.

TABLE I: Power Model Parameters for Different Node Types Used for WiMAX SLS at Variable Load

Node Type	$P_{max}$	$P_0$	$\Delta_p$	$P_{sleep}$
Base Station	20	130	4.7	75
BRT Station	0.5	9.75	3.5	6

The focal point is on BS and RS nodes consumption. Each node is made of multiple transceivers with multiple antennas. Each of these transceivers comprises a Power Amplifier (PA), a Radio Frequency (RF) small-signal transceiver section, a base-band interface (BB) and an overhead power. The overhead is produced from the DC-DC power supply, active cooling system and finally the main AC-DC power supply for connection to the electrical power grid. Note that active cooling is only relevant for the BS and it is neglected in the RS. Therefore, the total consumed power can be given as:

$$P_{TOTAL} = P_{BB} + P_{RF} + P_{PA} + P_{OVERHEAD} \quad (4)$$

The EARTH approach showed that both baseband as well as RF power consumption are scalable figures and can be modeled under the same form, more details on the scalable model can be found in [20].

### B. Power Consumption at Varying Load

The node load is defined by  $P_{out}/P_{max}$  which is proportional to the amount of utilized resources, comprising both data and control signals. Examination of the node power consumption as a function of its load reveals that mainly the PA scales with the load. However, this scaling over signal load largely depends on the node type. While the power consumption  $P_{in}$  is load-dependent for macro BS the dependency is less extent. Hence, a linear approximation of the node power model is justified [2]:

$$P_{TOTAL} = N_{TRX}P_0 + \Delta_p P_{out}, \quad P_{out} \leq P_{max} \quad (5)$$

where  $P_0$  is the power consumption at the minimum non-zero output power, and  $\Delta_p$  is the slope of the load-dependent power consumption. The parameters of the linear power model of [5] for BS and BRT RS are obtained by least squares curve fitting and are listed in Table I.

## IV. SYSTEM LEVEL SIMULATOR CONFIGURATION

The platform selected on this work to carry out the energy efficiency evaluation is a system level simulator of WiMAX standard [21]. The developed downlink SLS follows the guidelines provided by the evaluation methodology document [21] and compliant with the WiMAX IEEE 802.16m. In order for the system level simulator (SLS) to quantify the benefits of each link it needs a full set of link performance tables for different codeword sizes, code rates, and modulation schemes. A set of 48 Code Word Error Rate (CWER) versus the Signal to Noise Ratio (SNR) tables for the conventional turbo code (CTC) have been generated using the link levelcc simulator. This is in order to properly account for the performance of different resource allocations and physical layer configurations decided by the scheduler, which is the heart of any SLS.

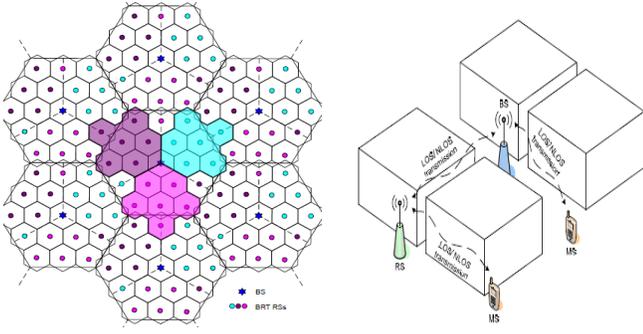


Fig. 2: Schematic of the WiMAX SLS relaying scheme Below Roof Top (BRT) [21].

### A. BRT Relaying Scenario

The WiMAX evaluation document [21] describes a number of relaying scenarios from which the BRT is considered in our evaluation. The BRT scenario as shown in Fig. 2 (right) assumes that the BS is located above rooftop while the RS are located below rooftop. In the BRT, the number of RSs deployed in each sector is six with omni-directional antennas for both relay (BS-RS) and access links (RS-MS). The RS antenna array broadside is assumed to be aligned with the LOS direction to the BS. Fig. 2 (left) shows the deployment of BRT RSs with six relays per sector for a 19 cell topology. The deployment looks like the hexagonal RS network with smaller cell sizes.

The relaying model implemented is defined as decode, store, encode, forward model. It is assumed that data transmitted on a relay link is decoded and potentially stored until a later frame. It is then encoded and transmitted on the next hop. MS associations are fixed for the duration of one snapshot trial. An MS is assigned to join with one node, either BS or RS, in a sector and this association is not changed during a trail. Access link transmissions from/to the BS and RSs within a sector occur on the same frequency but different times so called relay and access times. The scheduler adopted is proportional fair centralized scheduling where BS takes care of all resource repartition within its sector.

### B. Simulation Procedure

The functional diagram of the SLS simulation is presented below. It consists in a first loop on the number of snapshots where a given realization of MS dropping in the service area is generated, and a second loop where the DL transmission for the different active links is simulated.

The DL transmission first initializes parameters evolving along the transmission period (e.g. initial CQI values, initial average throughput, frequency noise generators, etc.). It then starts transmission frame per frame following the frame structure defined in the configuration and TDD duplex parameters. The traffic generation is first updated. Then the scheduler of each sector decides which resource units to be assigned to which active MS at which modulation and coding schemes. The transmission is then modeled by the channel pass, which first generates the fast fading physical channels for the links between the MS and its serving sector and dominant interfering sectors. The physical channels are then transformed

### Algorithm System Level Simulation Procedure

```

Start Monte Carlo Simulation
Simulation Configuration
Parameter Initialization
for snap-number of snapshots do
  MS dropping
  Start DL transmission
  for iter-number of frames do
    Traffic generation
    Scheduling
    Channel pass
    SINR computation
    CQI feedback calculation
    BLER estimation
  end for
  Store snapshot results
end for

```

TABLE II: BRT Relay Deployment Configuration [21].

Deployment Parameter	Value	
Number of RS per sector	6	
RS equipment	Relay Link	Access Link
RS maximum transmit power	27dBm	27dBm
Relay station antenna height	10m	10m
Number of transmit antennas	1	1
Number of receive antennas	1	1
Antenna type	Omni in horizontal p	Omni in horizontal p
Antenna gain (boresight)	7 dBi	7dBi
Noise figure	5dB	5dB
Cable loss	2dB	2dB

TABLE III: BRT Relay Path Loss and Channel Configuration [21].

Parameter	BS-RS link	RS-RS link	RS-MS link
Penetration Loss	0dB	0dB	LOS: 0dB & NLOS:10dB
Pathloss Model	Modified Baseline Model	Walfish-Ikegami LOS / NLOS	Modified Urban Microcell
Lognormal Shadowing Standard Deviation	6 dB and 2 dB mean	NLOS: 4dB / LOS: 3dB	NLOS: 4dB /LOS: 3dB
Correlation Distance for Shadowing	50m	NLOS: 12m / LOS: 14m	NLOS: 12m / LOS: 14m
Channel Mix	MVehA @30Kmh	MVehA @30Kmh	MVehA @30Kmh
Spatial Channel Model	Baseline model	Baseline model	Baseline model

into equivalent channels according to the sub-channelization configuration (thus performing the physical to logical sub-channels mapping).

The MS then computes the per data symbol post-processing SINR for the specified mode and all resource units over the whole bandwidth. It then determines the CQI per logical resource unit for feedback to the scheduler. The MS finally uses the link to system interface tables to estimate the FER associated with the current transmission. For BRT relays various system parameters need to be considered for the following links BS-RS, RS-RS and RS-MS. Table III summarizes the BRT relay path loss and channel configurations and Table II highlights the BRT relay deployment parameters.

## V. SIMULATION RESULTS

In this section we evaluate the performance of the two proposed back-pressure half and full duplex buffer aided

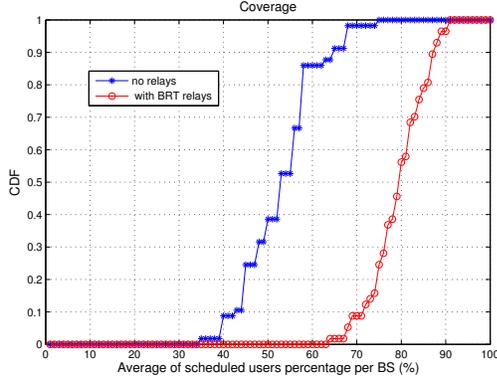


Fig. 3: The cumulative distributed function of the percentage of scheduled users of both BRT transmission with no relay selection and the non cooperative mode.

relay selection mechanisms. For this purpose we utilize the above developed WiMAX system level simulator. The utilized network topology is a 19 hexagonal cell layout where each cell is divided into three sectors. Each sector is associated by one macro BS. The BRT relaying scenario is adopted where six relays are deployed per sector as described in the previous section. We examine four relaying mechanisms using the same simulation configuration and assumptions described above. On the first mechanism no dynamic relay selection is used and MSs are associated with the same serving node either BS or RS for the whole transmission period, basically no dynamic relay selection is performed. For the second technique we deploy the conventional relay selection mechanism so-called max – min. In the max – min no buffer is required and the relay which provides maximum of the minimum channel quality index (CQI) of both BS-RS and RS-MS is selected. The third approach is the proposed half duplex relay selection (referred in plots by half duplex or BP 1/2) and finally the proposed relaying selection implemented in full duplex mode (referred in plots by full duplex or BP 1/1).

#### A. BRT scenario for $V = 0$ (maximum throughput)

Here we consider BRT with maximum throughput optimization problem ( $V = 0$ ) with the following main simulation parameters: 40 users per sector and 50 iterations.

Fig. 3 demonstrates the considerable coverage gain obtained by deploying BRT relays compared to the coverage obtained by the network without the assistance of relays. The latter emphasizes coverage as one of the main recognized benefits of deploying relays.

Fig. 4 represents the average throughput per user in kb/s of the different schemes of users (non proximal) which are a distance from the serving BS of 500m or more. As can be seen the full duplex relay selection showed significant increase of around 73% in terms of average throughput per user compared to the transmission scheme where no relays are deployed. The latter means a significant increase on the number of new connected users and noticeable enhancement of received service of the non-proximal users are achieved. The half duplex scheme came second and showed good improvement in terms of throughput. Now knowing the relayed schemes consume

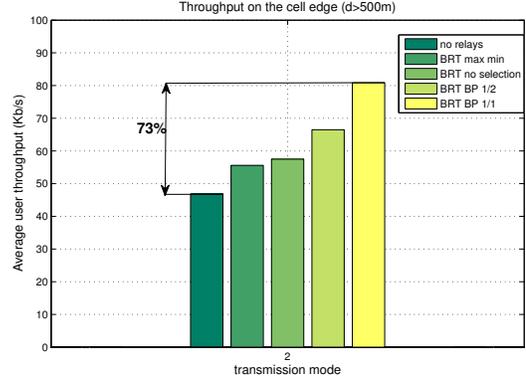


Fig. 4: Average throughput of edge users (distance from serving BS > 500m) of the five schemes.

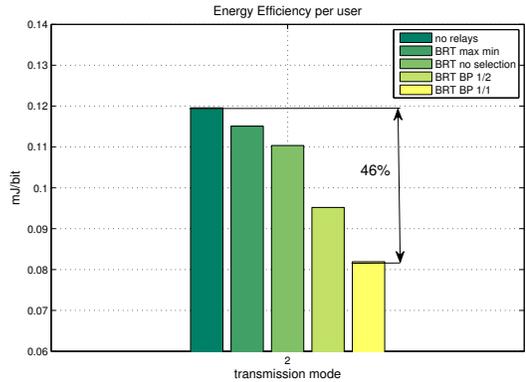


Fig. 5: The energy efficiency of the users at the edge of the five schemes.

extra power to run the deployed relay stations the question is are we gaining in terms energy efficiency considering the power framework adopted on this work?

Fig. 5 answers the latter question on which we can observe substantial gain of around of 46% on the average energy efficiency obtained when full duplex mode is activated compared to non cooperative mode where no relays are deployed. Note that the energy efficiency calculated here is the average energy required to serve users away from BS by 500m or more. The half duplex also showed a good efficiency better than BRT with no relay selection and max – min and the non cooperative scheme.

#### B. BRT scenario for $V > 0$

In the final experiment we try to show the impact of varying  $V$  on the performance of the full duplex mode coverage. Fig. 6 demonstrates the decrease of the network coverage in terms of cumulative distributed function when  $V$  increases from 0 to 100. The latter result mainly occurred because the network tends to drop more links while  $V$  increases. The dropped links are the more costly ones in terms of energy consumption, from which the two-hop links represent the majority. Therefore, for very high values of  $V$  the system is likely to drop all two hop links thus no relay assistance transmission is performed all together. An interesting extension of this experiment is

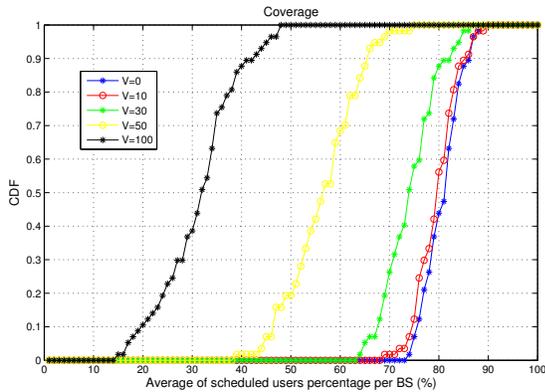


Fig. 6: The cumulative distributed function of the percentage of the scheduled users of BRT relaying for various values of weighting factor  $V$ .

to identify an optimum value of  $V$  on which the system performance in terms of energy efficiency can be optimized.

## VI. CONCLUSIONS & PERSPECTIVES

We proposed and evaluated two derivatives of a new relay selection mechanism in a WiMAX system level simulator in terms of energy efficient and throughput. The two mechanisms are half and full duplex buffer aided relay selection techniques derived from back-pressure algorithm. A holistic energy consumption model has been implemented to evaluate the energy efficiency of the cellular network. Considerable gains of around 76% in terms of throughput and 46% in terms of energy efficiency of users away from BS by 500m or more when full duplex scheme is deployed have been observed compared to non cooperative mode. Also it has been shown that by increasing the weighting factor  $V$  the system tends to conserve energy by dropping more two-hop transmissions where the network showed a tendency to operate in a non cooperative mode.

Interesting extensions of the presented work include identifying an optimum value of  $V$  on which the system performance in terms of energy efficiency is optimised. Also, since both LTE-A and WiMAX use OFDMA techniques for downlink and support reasonably similar relaying capabilities, implementing the proposed scheme into LTE-A system would sensible extension of this work.

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