Low ComplexityAdaptive Detection of Distributed SFBC in Open-Loop CoMP

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Abstract—**Coordinated multipoint (CoMP) is one technique that can be used to extend the coverage area by solving the Inter Cell Interference (ICI) problem occurring at the cell-edge. On the other hand, Distributed Space-Time/Frequency Block Coding (DSTBC/DSFBC) technique is used to improve the reliability in large modern wireless networks e.g. 3GPP LTE advanced. The cell-edge user is usually power limited. Hence, reducing processing load in such a terminal is preferable. In this paper, we propose a low complexity decoding method named Adaptive K-Best Sphere Decoder (AKBSD) to serve a high mobility cell edge user facing different varying frequency selective channels from multiple base stations. AKBSD adapts the number of K-paths the decoder processes while performing the tree search depending on the estimated received signal strengths and the channel quality of each transmission link in a DSFBC open-loop CoMP environment. The simulation results confirm a good trade-off between performance and complexity achieved by AKBSD under this scenario where about 20% reduction in complexity is achieved over a high K-value fixed KBSD for the price of 0.4 dB reduction in performance at BER value of 10^{-4}.**

***Keywords*—CoMP, K-Best Sphere Decoder, Adaptive decoding, Distributed STBC and SFBC.**

I. INTRODUCTION

Coordinated MultiPoint (CoMP) transmission has been considered in the 3GPP LTE Release 9 [1] then standardized in LTE-Advanced [2] as one technique used to improve the coverage area by changing the Inter Cell Interference (ICI) problem occurring at the cell-edge into a useful cooperation between the different cells [3]-[5]. The CoMP idea is to establish cooperation between various Base Stations (BSs) for collective signal processing in both up and downlinks [6], where each transmitting node sends its data based on scheduling information sent to it by a centralized Baseband Signalling Processing (BSP) unit [3]. The main categories of the downlink CoMP (DL-CoMP) are summarized Fig. 1 [3]-[5].

In Coordinated Scheduling/Beamforming (CoMP-CBF), each BS (or Remote Radio Equipment (RRE)) transmits beamformed signal for the cell-edge user in its serving cell only. This results in reduced ICI. In Joint Processing/Transmission (CoMP-JP), eNodeB controls the transmission of the cell-edge user data symbols, transmitted from all RREs at the same time then this data is jointly processed across the PREs. CoMP-JP is further divided into two categories. The first category is Joint Transmission (JT) where the same data is transmitted from multiple serving cells (coordinated cells) as well as non-serving cells [4]. In JT, one transmission scheme is Local Precoding (LP) in which multiple BSs transmit the same cell-edge user signal, which is separately precoded. Another scheme is Global Precoding (GP) where the channel matrices for the multiple BSs are aggregated as $\mathbf{H}_{\mathbf{global}} = [\mathbf{H_1}\ \mathbf{H_2}..\ ]$ where $\mathbf{H_i}$ is the channel matrix associated with BS_i. The GP scheme is considered as a generalization of single-cell multi-antenna transmission to antenna ports of more than one cell [5]. The second category is Dynamic Cell Selection (D-CS), where a dynamic fast scheduling at the central BS is responsible for selecting one base station to transmit the data block.

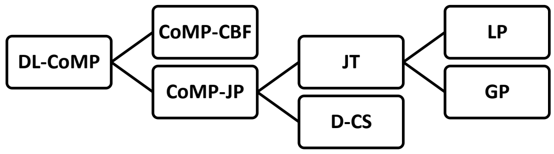

Fig. 1 Downlink CoMP categories.

Another technique used to improve the reliability in large wireless networks, e.g. Relay-Assisted Communication (RAC), is Distributed Space-Time/Frequency Block Coding (DSTBC/DSFBC). RAC is introduced to cellular systems to improve the performance of cell-edge users and is recommended in modern wireless standards e.g. 3GPP LTE-Advanced [7]. In DSFBC multiple transmission nodes are used together in a distributed way to transmit a Space Frequency Block Codes (SFBC) to the cell-edge user, this redundancy in space and frequency increases the reliability of the communication in OFDM systems by increasing the diversity gain.

In high mobility cell-edge user scenario, the channels between the BSs and the Mobile Station (MS) are time varying. Moreover, sending high data rates and the existence of different delayed paths of the signal give rise to frequency selective channels. These dynamic channels require more sophisticated decoding algorithms in the receiver in contrast to the case of quasi-static channels, in which the channel is assumed to be constant over a block of transmitted symbols and hence a linear decoding is sufficient in the signal detection processing. Therefore, the assumption of quasi-static channels is not realistic in this scenario and non-linear decoding algorithms are needed to decode the SFBC at the MS. However, these algorithms require excessive computational complexity. Maximum-Likelihood (ML) detection is the exhaustive optimum detector. However, it has an exponential increase in complexity for QAM modulation schemes which makes its implementation impractical. Classical K-Best Sphere Decoder (KBSD) is a fixed complexity type of Sphere Decoding (SD) algorithms that perform search within a sphere around the received vector to reach the ML solution instead of the exhaustive search, which results in a large complexity reduction. Nevertheless, the fixed value of the K-paths used in the KBSD is not always suitable for all the system operation conditions such as the dynamically conditions of the high mobility cell-edge user scenario. In addition, the MS is usually a battery-based device and the power consumption is an important aspect that should be taken into account. Therefore, reducing the computational complexity in that terminal is highly needed.

In this paper, we use the DSFBC as a transmit diversity technique which distributes the SFBC codeword among different transmission BSs in an open-loop CoMP scheme. The scenario we consider is the realistic case of two time varying frequency selective channels, in which case the simple linear decoder basic assumption of static channel over two frequency symbols no longer holds. We propose to decode the combined signal at the user node by Adaptive KBSD (AKBSD), which is a low complexity decoding algorithm suitable for such an environment. It modifies the fixed K-paths traditional K-Best sphere decoder into an adaptive one. The proposed adaptive scheme, adapts the number of K-paths that the decoder processes while exploring the tree search depending on the channel quality of each transmission link. The selectivity of each channel and the received signal strength are measured and a suitable K-value is assigned for different equivalent tree levels to search among them separately. This gives a lower complexity decoding processing which maintains the power in a cell-edge user. Using AKBSD decoder helps to reduce the large computational processing associated with the CoMP technique at the MS. Therefore, it encourages the CoMP operation in varying channels.

The rest of the paper is organized as follows: in section II the system model of the CoMP DSFBC in an open-loop scenario is presented. Section III proposes how the AKBSD works while section IV shows the simulation results of the performance and the complexity in terms of the average number of Visited Nodes (VN). Finally, the paper is concluded in section V.

II. CoMP DSFBC SCENARIO

The system model that we work on is shown in Fig. 2. BS_1 and BS_2 are two base stations covering two coordinated serving cells and MS_1 is a cell-edge mobile user. The general communication between the two base stations and the mobile MS_1 can be viewed as 2×1 Multiple Input Single Output (MISO) system. Data symbols $X_1, X_2, \dots, X_i, \dots, X_{Nc}$ from the constellation set $\mathbb{C}$ are sent over subcarriers $1, 2, \dots, i, \dots, N_c$ respectively of an OFDM system and N_c is the number of used subcarriers.

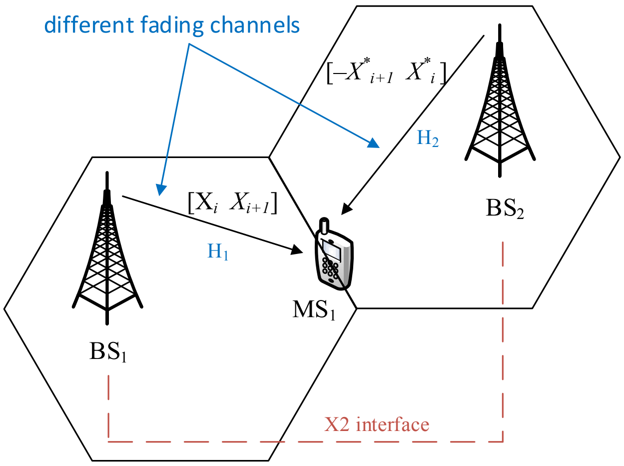

Fig. 2 System model.

A distributed Alamouti codeword [8] is spread between the BSs as shown in Fig. 2 where one BS transmits $[X_i\ \ X_{i+1}]$ and the other transmits $[-X^*_{i+1}\ \ X_i{}^*]$ over two different frequency selective fading channels. The whole codeword matrix for a pair of cells is given by [3]

$$\mathbf{X} = \begin{bmatrix} X_i & X_{i+1} \\ -X^*_{i+1} & X_i{}^* \end{bmatrix} \tag{1}$$

where $i = 1, 2, \dots, N_c - 1$ and $(.)^*$ denote conjugate operation while the columns represent the data carriers and the rows represent each BS antenna. Assuming a perfect Channel State Information (CSI) is available at MS_1, the received signal in the frequency domain takes the general form $Y = \boldsymbol{H}\, X + N$ as

$$\begin{bmatrix} Y_1 \\ Y_2^* \end{bmatrix} = \begin{bmatrix} H_{11} & -H_{21} \\ H_{22}^* & H_{12}^* \end{bmatrix} \begin{bmatrix} X_1 \\ X_2^* \end{bmatrix} + \begin{bmatrix} N_1 \\ N_2^* \end{bmatrix} \tag{2}$$

where N is additive white Gaussian noise and H_{jk} is the coefficients of the two different frequency selective fading channels and $j=1,2$ represents the channel associated with j^{th} BS and $k=1,2\dots N_c$ represents the subcarrier associated with current pair of cells in the decoding process.

In our model, the cell-edge mobile station, i.e. MS_1, uses SD in the decoding process over pair of cells. SD considers only the vectors inside a sphere with radius R_{SD} with upper limit of

$$arg\ min_{X\in\mathbb{C}}\ \|Y - \boldsymbol{H}X\|^2 \le R_{SD}{}^2. \tag{3}$$

It converts the underlying complex system into an equivalent real one by separating the real and imaginary parts of each complex component and the equivalent system is written as

$$\bar{Y} = \bar{\boldsymbol{H}}\bar{X} + \bar{N}\ . \tag{4}$$

The SD search is represented as a tree search and the KBSD [9] is based on a breadth-first algorithm that makes search in the forward direction only. Using QR decomposition, we get $\bar{\boldsymbol{H}} = \boldsymbol{QR}$, where **R** is an upper triangle matrix with positive diagonal elements, **Q** is an orthogonal matrix and $\tilde{Y} = \boldsymbol{Q}^H \bar{Y}$. The system can now be written as

$$arg\ min_{\bar{X}\in\mathbb{C}} \left\|\tilde{Y} - \boldsymbol{R}\bar{X}\right\|^2 \le R_{\mathrm{SD}}{}^2 \quad (5)$$

and
$$\left\|\tilde{Y} - \bar{\boldsymbol{R}}\bar{X}\right\|^2 = \sum_{m=1}^{2Nt} d\left(\bar{X}_m^{2N_t}\right) \le R_{\mathrm{SD}}{}^2 \quad (6)$$

where $d(\bar{X}_m^{2N_t})$is the squared Partial Euclidean Distance (PED) of $\bar{X}_m^{2N_t}$ (symbols ordered from m to $2N_t$) where N_t is the number of transmitted antennas and is calculated recursively by [9]

$$d\left(\bar{X}_m^{2N_t}\right) = d\left(\bar{X}_{m+1}^{2N_t}\right) + \left|\tilde{Y}_i - \sum_{p=m}^{2N_t} R_{mk}\bar{X}_k\right|^2 \quad (7)$$

and R_{mp} is the $(m,p)^{\text{th}}$ element of **R** and $m= 2N_t, \ldots ,1$.

III. ADAPTIVE KBSD

KBSD is a tree search and its complexity and performance depends on the chosen parameter K where the higher the K, the higher the performance and the complexity and vice versa. Therefore, a trade-off between performance and complexity exists. An optimum value of the K is required. However, a fixed value is not always the optimum value for a varying environment. Thus, adapting the K-value according to the varying conditions is one solution. Two criteria are proposed in [10] and [11] to adapt the K-value. The first one was inspired by [12] and is based on estimating the channel quality by measuring the channel selectivity and then a suitable K-value is passed to the KBSD to search the whole tree using it. The second criterion is based on estimating the strength of each received symbol by calculating the deviation of each channel matrix column norm from the ideal column norm value.

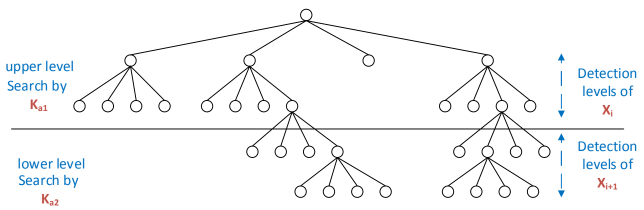

Fig. 3 Different K-values are assigned for different levels of the tree.

In this paper, we use the same concept of measuring the channel selectivity as in [10] and [11] but for each channel separately. The algorithm used here estimates the selectivity of the two channels together and combines it with the estimated received signal strength to select one suitable K-value to be passed to the KBSD. This combined decision takes into consideration the effect of the two channels on the multiple versions of the same symbol which are transmitted from the two BSs according to the codeword in equation (1) and then select an appropriate K-value to search the equivalent levels of the tree which related to that transmitted symbol and therefore two values of K (ka_1 and ka_2) are used while exploring the tree as shown in Fig. 3, where the upper levels represent the detection levels of the symbol X_i while the lower levels represent those of X_{i+1}.

The steps used in the decoding process are as follows:

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for each pair of cells,
do:
Preprocess:
define $m_{ideal} = \|[1\ 1]^T\| = \|[-1\ 1]^T\| = 1.4142$
define $m_{th1} = m_{ideal} + \delta$ *and* $m_{th2} = m_{ideal} - \delta$
calculate $m_i = \|\boldsymbol{H}(:,i)\|$ $\forall i=1,2$
calculate $C_i = \frac{min\ (H_{i,j}\ ,\ H_{i,j+1})}{max\ (H_{i,j}\ ,\ H_{i,j+1})}$ $\forall i=1,2\ ; j=1:N_c-1$
if $C_i > \Gamma$ *and* $m_{th1} < m_i < m_{th2}$
    $k_{ai}=k_1;$
else if $C_i < \Gamma$ *and* $m_{th1} < m_i < m_{th22}$
    $k_{ai}=k_2;$
else
    $k_{ai}=k_3;$
end if
Search the tree:
start from root level
initialize a zero metric path between the root and the first tree level nodes
<u>loop:</u>
extend the survivor paths and update their PEDs
if upper level
    set $k=k_{a1};$
end if
if lower level
    set $k=k_{a2};$
end if
sort and select the K-Best PEDs and discard the others
if leaves level is reached
    exit
else
    go back to loop
end if
end

For the first pair of cells, the channel between the two BSs and the MS after applying the DSFBC at the BSs as shown in Fig. 2 can be written as

$$\mathbf{H} = \begin{bmatrix} H_{11} & -H_{21} \\ H_{22}^* & H_{12}^* \end{bmatrix} \quad (8)$$

The two C parameters are calculated as

$$C_1 = \frac{min\ (H_{1,k}\ ,\ H_{1,k+1})}{max\ (H_{1,k}\ ,\ H_{1,k+1})}\ \&\ C_2 = \frac{min\ (H_{2,k}\ ,\ H_{2,k+1})}{max\ (H_{2,k}\ ,\ H_{2,k+1})} \quad (9)$$

where $H_{j,k}$ is the channel coefficient for j^{th} BS at the k^{th} subcarrier i.e.$C_1 = \frac{min\ (H_{11}\ ,\ H_{12})}{max\ (H_{11}\ ,\ H_{12})}$ & $C_2 = \frac{min\ (H_{21}\ ,\ H_{22})}{max\ (H_{21}\ ,\ H_{22})}$.

The two columns norms are calculated as

$$m_1 = \|\boldsymbol{H}(:,1)\| = \|[H_{11}\ H_{22}^*]^T\|,$$
$$m_2 = \|\boldsymbol{H}(:,2)\| = \|[-H_{21}\ H_{12}^*]^T\|. \quad (10)$$

Using the ideal channel $\mathbf{H}_{\text{ideal}} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$, we can calculate its ideal column norm $m_{ideal} = \|[1\ 1]^T\| = \|[-1\ 1]^T\| = 1.4142$ and use it with the defined threshold value δ to estimate the strength of the received symbol by defining two boundaries $m_{th1} = m_{\ ideal} + \delta$ and $m_{th2} = m_{\ ideal} - \delta$, and if m_1 or m_2 lies between these boundaries, the current signal strength is near the transmitted one and hence the channel has a little effect on it i.e. the channel is in good quality state, and if m_1 or m_2 lies outside these boundaries, the channel is in bad quality state and has high effect on the transmitted signals.

If C_1 is greater than threshold Γ and $m_{th1} < m_i < m_{th2}$ then we will search the upper level of the tree with a small K-value as the channel is most likely non-frequency selective or facing a small fading conditions and the symbol strength is high as well and if $C_1 < \Gamma$ and $m_{th1} < m_i < m_{th2}$ then the channel is somehow frequency selective but symbol strength is still high then an intermediate K-value is needed. Otherwise, a high K-value is required to compensate for the high selectivity of the channel and the symbol weakness. The same is done for the lower level of the tree search depending on the value of C_2.

IV. Simulation Results

The system model in Fig.2 was simulated using16-QAM and 64-QAM modulation schemes under frequency selective fading channels between the BSs and the MS_1. The model assumes perfect CSI at MS_1. Increasing the K-value passed to the KBSD increases its performance as shown in Fig. 4 in which different K-values were passed to the KBSD for the 16-QAM and 64-QAM modulation schemes and each higher K-value gives lower BER at the same SNR. The ML optimum detector was plotted as well. To clarify the performance-complexity trade-off, two BER values (at SNR = 15 dB and 21 dB) are plotted against the average number of visited nodes, i.e. VN, at different K-values for 16-QAM as shown in Fig. 5, where increasing the number of K-values increases the performance (decreases the BER curve) but increases the complexity (increases the average number of VN curve).

The AKBSD performance depends on the selection of the threshold value Γ provides the best trade-off between performance and complexity. We calculated the average number of VN as an indication of the computational operations involved, and the equivalent BER values at a working SNR of 15 dB. We assume hard decoding in our system i.e. no channel coding was implemented here. Normalized values are plotted in Fig. 6 and the value of Γ that achieves the best BER/VN trade-off is 0.82 with a loss of performance of only 1×10^{-4}.

Using Γ=0.82 as a threshold value in the AKBSD and δ = 0.3 (selected based on a similar numerical analysis as that used for the Γ selection), a comparison between the performance of two fixed K-values KBSD (with K=2, 16 for 16-QAM and K=4, 44 for 64-QAM) and the AKBSD is done as shown in Fig. 7. The lower fixed K-values are selected for

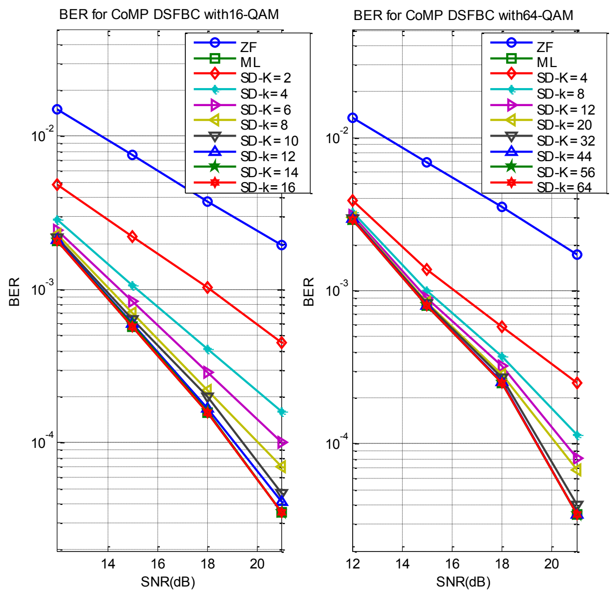

Fig. 4 BER performance for different K-values of KBSD.

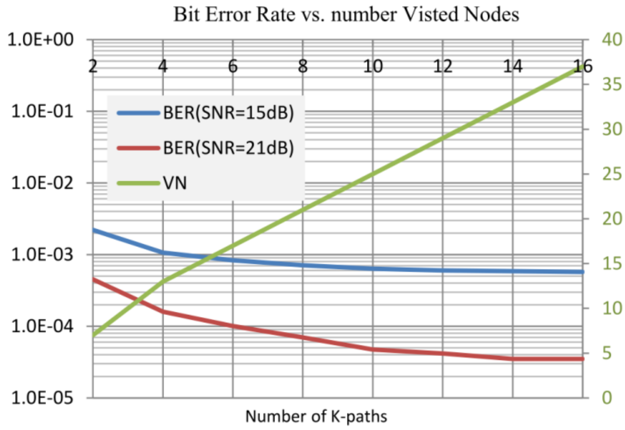

Fig. 5 The trade-off between the performance (BER) and complexity (in terms of the number visited nodes) for 16-QAM.

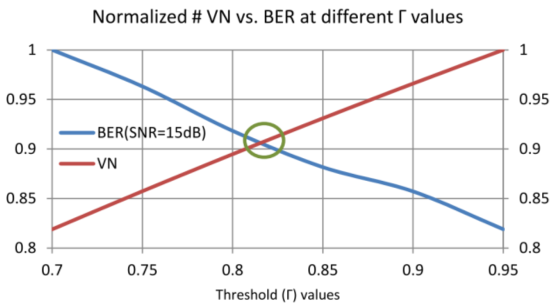

Fig. 6 Normalized curve of number of VN and BER values at a working SNR of 15 dBfor 16-QAM at different Γ values.

comparison because they give the lower complexity while the upper are selected as they give almost the ML performance and any increase in K-value after them is just an increase in complexity without any performance gains. The AKBSD gives a performance that is very near to the higher K-value KBSD in both the 16-QAM and 64-QAM modulation schemes. One possible measurement of the complexity is the average number of VN in the tree during the search process of the various decoding algorithms and its results are summarized in Table I.

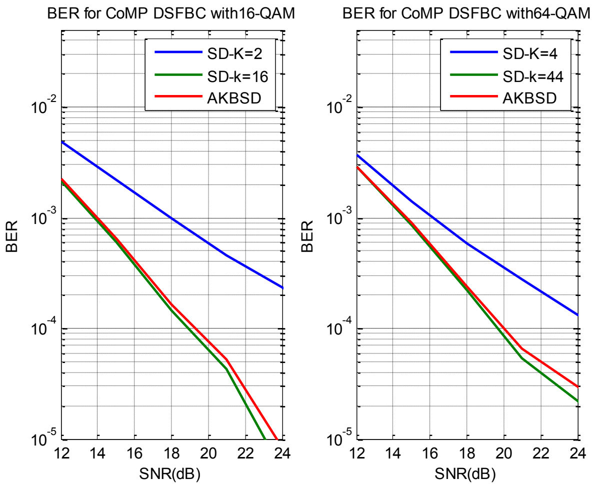

Fig. 7 BER performance of AKBSD.

TABLE I. AVERAGE NUMBER OF VISITED NODES

Decoding method	# visited nodes	
	16-QAM	**64-QAM**
KBSD(K_1)	(K_1=2) 7	(K_1=4) 26
KBSD(K_2)	(K_2=16) 37	(K_2=44)194
ML	85	1170
AKBSD(Γ=0.82)	30	129

As shown in Fig. 7 and Table I, the AKBSD requires much lower number of VN than ML and a considerable lower number than the higher K-value KBSD (K=16 for 16-QAM and K=44 for 64-QAM scheme) e.g. at a target BER of 10^{-4}, about 33.5 % reduction for the 64-QAM scheme and 18.9% for the 16-QAM scheme obtained with loss of performance of only 0.37 dB and 0.4 dB respectively. Therefore, the AKBSD in such a scenario can be used to offer coverage to the cell-edge user with lower complexity decoding which in its turn reduce the power consumption. This is especially valuable for handheld battery-based devices.

V. CONCLUSIONS

In this paper we propose an AKBSD low complexity decoder for distributed SFBC in a CoMP environment. CoMP can be used to improve the coverage at the cell-edge. In addition, employing DSFBC improves the reliability in modern wireless standards. However, the battery-based devices are challenged by the power consumption needed to perform the detection and decoding operations. The AKBSD changes the number of paths that the decoder processes in a tree-based search according to the estimated received signal strengths and the quality of the channel. The value of each BS channel selectivity is estimated and the corresponding part of the tree is searched by a suitable value for this channel quality. By utilizing such approach, the AKBSD achieves a considerable complexity reduction corresponding to low computational load at the mobile terminal while still providing a good performance.

ACKNOWLEDGMENT

This research was supported by the Ministry of Higher Education (MoHE) of Egypt through Ph.D. fellowships with E-JUST University programs.

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