STAC: Simultaneous Transmitting and Air Computing in Wireless Data Center Networks

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Abstract—The data center network (DCN), wired or wireless, features large amounts of Many-to-One (M2O) sessions. Each M2O session is currently established using Point-to-Point (P2P) communications and Store-and-Forward (SAF) relays, and is generally followed by a certain computation at the destination, typically a weighted summation of the received information digits. Fundamentally different from this separate P2P/SAF-based-transmission and computation framework, this paper proposes STAC, a novel physical layer scheme that achieves Simultaneous Transmission and Air Computation in wireless DCNs. In particular, STAC builds on a number of distinguishing characteristics of DCs to take advantage of the superposition nature of electromagnetic signals. With STAC, multiple sources transmit in the same time slot with appropriately chosen parameters, such that the superimposed signal can be directly transformed to the desired summation at the receiver. To enable STAC, we propose an enhanced Software Defined Network (SDN) architecture, where a wired low-bandwidth backbone provides wireless transceivers with external reference signals. Theoretical analysis and simulation results show that STAC can significantly improve both bandwidth and energy efficiency in DCNs.

I. INTRODUCTION

A modern Data Center (DC) typically consists of a large dedicated cluster of commercial computers (work nodes) that are housed together to store/process big files in a parallel manner. The parallel storage/processing of the files necessitates frequent communication among the work nodes, which is accomplished through the Data Center Network (DCN).

Despite the maturity in deployment and their high bandwidth, there are a few critical problems associated with wired DCNs, such as limited flexibility, cabling complexity, operation cost, etc. These problems significantly limit the scalability of DCNs and are being exacerbated by the huge amount of data that needs to be stored/processed within a DC and exchanged through the DCN in today’s age of big data.

To overcome these limitations, recent works [1]–[6] explore the possibility of constructing wireless DCNs using high frequency electromagnetic (EM) signalling. 60 GHz techniques are proposed for realizing wireless DCN links with bandwidth comparable to wireline connections in [1], [2], while the blockage and directivity problems associated with EM waves can be significantly mitigated by utilizing strategies like ceiling reflection and 3D beamforming [3]. Free-space optical DCN communication has also been investigated, and shown to achieve further improvements in bandwidth and nearly perfect directivity [4]. On the other hand, [5] considers augmenting the wired DCN with wireless flyways, and [6] demonstrates that a completely wireless DCN with a Cayley structure is feasible and performs even better than a wired DCN.

A. Challenging the P2P and SAF Paradigm

This paper aims to further the research of wireless DCNs by challenging two of its fundamental assumptions, namely, Point-to-Point (P2P) communication and Store-and-Forward (SAF) relaying. These two paradigms form the basis of today’s ubiquitous wireless networks, e.g., cellular and 802.11 networks, but here we argue that they may be highly suboptimal for DCNs due to a number of distinguishing characteristics of the traffic and the computations typically occurring within DCs.

First, the DCNs feature a large number of Many-to-One (M2O) sessions arising from various DC applications, e.g., Google File System (GFS) [7] and MapReduce [8]. Due to the limited transmission range of high frequency EM waves, these M2O sessions are established through multi-hopping over hierarchical multiple-access units as shown in Fig. 1, where each hop is based on P2P communication followed by SAF relaying onto the next hop. Specifically, with Time Division Multiple-Access (TDMA) inside the multiple-access
unit, the source nodes 1, 2, \ldots, K successively transmit their information to the relay node 0 in different time slots via P2P transmissions, and the relay stores the received information in its buffer before forwarding them to the destination d. Since node 0’s buffer and input/output bandwidth are shared by all the K source nodes, the performance of this approach can be poor, especially when K is large. Indeed, the problem gets worse as we get closer to the destination, since the information to be transmitted accumulates along the way.

Another important characteristic of DCs is that the M2O sessions are generally followed by certain computations at the destination nodes. These computations normally satisfy the commutative and associative operational laws, with weighted summation being the typical case (e.g., in linear network coded storage [9] and MapReduce-based machine learning [10] applications). This opens up the possibility of dividing a large computation task into several sub-tasks that can be conducted at the intermediate relay nodes, rather than demanding the final destination do all the computation. In other words, instead of forwarding all the received digits, the relay could perform some intermediate computation and then forward only the output of the computation, thereby utilizing the bandwidth more efficiently. Considering that the bottleneck lies in the DCN scalability, not the compute capabilities of the works nodes, we believe that such a Compute-and-Forward (CAF) approach can be highly preferable to traditional SAF relaying in DCNs.

B. A New Scheme: STAC

Based on the above observations, two natural suggestions to improve the performance of P2P and SAF based DCNs can be the following:

1) The sources can transmit their digits in the same time slot, and the receiver can recover the digits based on multi-user detection.

2) The relay can perform computation (weighted summation typically) of the recovered digits, and then forward the computation result onto the next hop.

In this paper, we go one step further. We propose a new physical layer scheme, dubbed STAC (Simultaneous Transmission and Air Computation), which takes advantage of the superposition nature of EM signals and can achieve the above described two functions simultaneously over the air.

With computation task division, it suffices to illustrate STAC for a particular multiple-access unit as depicted in Fig. 1. Suppose that the receive node 0 is only interested in the weighted summation $s_0$ of the $K$ source digits $s_1, s_2, \ldots, s_K$,

$$s_0 = \sum_{i=1}^{K} w_is_i, \quad (1)$$

where $w_1, w_2, \ldots, w_K$ are the weight coefficients which are assumed to be real integers throughout this paper. In STAC, the $K$ source nodes transmit their digits in the same time slot with appropriately chosen transmit powers, frequencies, phases and times, such that their information bearing EM signals arrive at node 0 in a desired superimposed form that can be transformed to $s_0$ directly. We will show that STAC significantly improves bandwidth and energy efficiencies over the separation based approach for transmission and computation as it effectively allows to communicate only the desired computation and not the constituent digits to the receiver. Note that given $s_1, s_2, \ldots, s_K$, we can always find $s_0$ but not vice versa, so the information content of $s_0$ can be much smaller than the total information contained in $s_1, s_2, \ldots, s_K$. Additionally, in the general case when node 0 needs to fully recover the original $K$ source digits, e.g., for performing some computation other than weighted summation, one can still apply STAC by properly designing a set of pseudo coefficients $\{w_1, w_2, \ldots, w_K\}$ such that the original digits $s_1, s_2, \ldots, s_K$ can be extracted from the received $s_0$. In other words, STAC subsumes multi-user detection as a special case.

To enable STAC, accurate channel state information (CSI) and perfect frequency/time synchronization among the transceivers are needed, both of which may be difficult to obtain in general wireless networks. Thanks to the indirect ceiling-reflected Line of Sight (LoS) channel [3] and fixed locations of the transceivers, however, the CSI in a DC is nearly time-invariant and can be accurately estimated. To accomplish the synchronization, on the other hand, this paper proposes to use wired connections among all the work nodes to provide the wireless transceivers with external reference signals (e.g., a high quality external clock signal) [11], based on an enhanced Software Defined Network (SDN) architecture [12].

It should be pointed out that, the wired connections here are distinguished from the information transmission links in a wired DCN. The former are dedicated and solely responsible for control signals, not requiring the high bandwidth as in the latter, and thus will not cause the aforementioned problems encountered by wired DCNs. We also remark that to build up such a wired control network in DCs is plausible considering that the work nodes are usually compactly piled up in a dedicated room of limited size. As a by-product, it will also reduce the DCN operation cost by eliminating the need of using individual oscillators at the transceivers.

II. MOTIVATING EXAMPLES

Two major DC applications are i) distributed file storage, e.g., GFS [7] and Hadoop Distributed File System (HDFS) [13], and ii) parallel big data processing based on the MapReduce model [8]. We now present three detailed DC application examples mentioned in Section 1 that motivate STAC, where the first two correspond to GFS and MapReduce, respectively, and the last one shows the flexibility of STAC for general applications. Again, with task division, we can concentrate our discussion on the multiple-access unit depicted in Fig. 1.

Network Coded Storage. Due to the nonnegligible node failures in a DC [7], in distributed storage systems, a big file is usually divided into many fixed-length data blocks that are further protected by multiple replicas stored at different work nodes.
For storage efficiency, a network code can be applied [9], [14], [15], where each node stores network coded blocks instead of raw data. When a coded block is lost due to a node failure, it can be reconstructed at another node by performing the following algorithm on a digit-by-digit basis:

Algorithm 1 Network Coded Recovery

1: $s_0 = \sum_{i=1}^{K} w_i s_i$
2: $s_0 \leftarrow s_0 \mod 2^q$

where $s_0$ denotes a digit from the lost coded block requiring recovery, $s_1, s_2, \ldots, s_K$ are digits from the data blocks stored at the other nodes, $w_1, w_2, \ldots, w_K$ are the network coding coefficients, and the modulo operation is due to the finite field size $2^q$. Clearly, with STAC, we can achieve Step 1 of the algorithm directly.

MapReduce Based Data Processing. In MapReduce model, when the map nodes finish the processing, their outputs with the same key will be sent to a specified reduce node for the final computations. Such computations are also typically in the form of weighted summations [8], [16], e.g., for all machine learning algorithms fitting the statistical query model [10], scientific processes [17], [18], documents similarity comparisons [19], etc. Again, STAC can be applied to achieve simultaneous transmission and computation here.

General Case. When the receive node 0 needs the original source digits, one can appropriately design a set of pseudo coefficients $\{w_1, w_2, \ldots, w_K\}$ such that the source digits $s_1, s_2, \ldots, s_K$ can be extracted from $s_0$. In particular, suppose for each $i = 1, 2, \ldots, K$,

$$0 \leq s_i \leq 2^q - 1,$$

then choosing $w_i = 2^q(i-1)$ yields

$$s_0 = \sum_{i=1}^{K} 2^q(i-1) s_i,$$

based on which all the source digits can be extracted with the following algorithm:

Algorithm 2 Source Digits Extraction

1: $i \leftarrow 1$
2: while $i \leq K$ do
3: $s_i \leftarrow s_0 \mod 2^q$
4: $s_0 \leftarrow (s_0 - s_i)/2^q$
5: $i \leftarrow i + 1$
6: end while

III. SYSTEM ARCHITECTURE WITH STAC

This section describes the system architecture with STAC. We first introduce the principle of a basic STAC unit, and then propose an enhanced SDN architecture that enables the functioning of DCNs with STAC units.

A. A Basic STAC Unit

STAC is a general physical layer scheme that can be applied to wireless DCs with any structure, carrier frequency, etc. For illustration, consider a typical layout of the wireless DC as shown in Fig. 2, where each rack contains multiple work nodes and has an antenna array mounted on its top to communicate with other racks (communications within a rack are accomplished with intra-rack connections) [6]. As in [3], ceiling-reflecting and 3D beamforming techniques are adopted to achieve an indirect LoS link between any two antenna arrays without causing interference to others.

Suppose $K$ work nodes (in $K$ different racks) need to transmit their digits $s_1, s_2, \ldots, s_K$ to node 0 for computing the weighted summation as in (1). The operating principle of STAC is illustrated in the following.

Each source node $i$ maps its digit $s_i$ to a baseband modulated complex symbol $d_i$, and then up converts the symbol $d_i$ to a passband signal given by

$$\sqrt{P_i} e^{-j\theta_i} d_i(t)e^{-j\theta_{0}},$$

where $\theta_i$ and $\sqrt{P_i}$ are the pre-equalizing phase and amplitude coefficients, respectively. Suppose each node $i$ transmits at time $t_i$ using 3D beamforming, then the received passband signal $y(t)$ can be expressed as

$$\sum_{i=1}^{K} h_i e^{j\theta_i'} \sqrt{P_i} e^{-j\theta_0} d_i(t - t_i - \tau_i) e^{-j\theta_{0}'} (t - t_0 - \tau_i) + n(t),$$

where $h_i e^{j\theta_i'}$ is the equivalent complex channel coefficient from node $i$ to 0, $\tau_i$ is the propagation delay for node $i$, and $n(t)$ is a Gaussian noise of variance $\sigma^2$ for both the real and imaginary dimensions. With accurate CSI, one can set

$$\theta_i' = \theta_i$$

and $t_i = t_0 - \tau_i$,

such that the received signal simplifies to

$$y(t) = \sum_{i=1}^{K} h_i \sqrt{P_i} d_i(t - t_0) e^{-j\theta_{0}'} (t - t_0) + n(t),$$

which, after down conversion and sampling at time $t = t_0$,
yields the baseband symbol\(^1\)

\[ y = \sum_{i=1}^{K} h_i \sqrt{P_i} d_i + n. \tag{3} \]

Clearly, if each node \( i \) sets

\[ P_i = (w_i / h_i)^2, \tag{4} \]

then after eliminating the noise, node 0 can construct the desired digit \( s_0 \) as in (1) from the symbol \( y \) in (3).

With the above described principle, we find that the time/frequency synchronization and pre-equalization, such as (2) and (4), are essential for STAC. They can be realized by using an enhanced SDN architecture as we discuss next.

**B. An Enhanced SDN Architecture**

The DC generally work based on centralized control, where the front servers, including the job scheduler and data manager, control all the work nodes. In current DCNs, control signals and data traffic share the same network. Here, we propose to use a dedicated low bandwidth wired control network with an added network server as shown in Fig. 3, based on an enhanced SDN architecture. As mentioned in Section 1, the wired control network is feasible due to limited DC size and fixed node locations.

Our SDN architecture is an enhanced one in the sense that it not only accomplishes networking control as in general SDNs, but also also provides the wireless transceivers the physical and upper layer configurations to enable STAC, including the synchronization information, the physical layer parameters such as powers, frequencies, phases and times, and the scheduling/routing information.

**Synchronization with External Reference Signals:** External reference signals are provided to all the transceivers for synchronization. These include a high quality external clock signal, with which individual crystal oscillators at the transceivers are no longer needed and the operation cost can be thereby reduced. These reference signals can also help calibrate the wireless transceivers, e.g., reduce the errors induced from the device hardware differences [11].

**Physical Layer Parameters:** The network server maintains a connection information table that stores important physical layer parameters for each connection, such as the transmission delay \( \tau \), channel coefficient \( h e^{-j \beta} \) and the steering vectors required for 3D beamforming. When a transceiver fails (or a new one comes in), it informs the network server through the control network and the connection information table is updated.

**Scheduling/Routing:** Also maintained by the network server is a table storing the scheduling/routing information. When a current task finishes or a new one needs to start, the job scheduler informs the network server to update the scheduling/routing information table. Then the network server initiates the needed coordinations between the work nodes involved.

**IV. PHYSICAL LAYER ISSUES**

**A. Modulation-Demodulation Mapping**

The modulation for STAC is the same as that for P2P channels. However, their demodulation mappings are subtly different: STAC demodulation maps a superimposed symbol, to the summation of the digits, whereas the P2P channel demodulation maps a particular symbol from the transmit symbol set to the corresponding digit.

**STAC Modulation.** Specifically, writing node \( i \)'s digit \( s_i \) into the bit sequence form yields

\[ [s_i(1), s_i(2), \ldots, s_i(l), \ldots, s_i(L)] \]

where \( s_i(l) \) is the \( l \)-th bit, \( L \) is the sequence length, and

\[ s_i = \sum_{l=0}^{L-1} 2^l s_i(l). \]

For modulation, assume BPSK (Binary Phase Shift Keying)\(^2\) without error correction coding throughout this paper. At node \( i \), each bit \( s_i(l) \) is modulated to a symbol \( d_i(l) \in \{ -1, +1 \} \) as \( d_i(l) = 1 - 2 \times s_i(l) \).

**STAC Demodulation.** After the \( l \)-th transmission and the removal of noise with signal detection, the received superimposed symbol can be written as

\[ y(l) = \sum_{i=1}^{K} h_i \sqrt{P_i} d_i(l) \tag{5} \]

By setting the transmit power\(^3\) \( P_i = (w_i / h_i)^2 \), one has

\[ y(l) = \sum_{i=1}^{K} w_i d_i(l), \tag{6} \]

\(^1\)The \( h_i \) in (3) are real variables, so that the real and imaginary parts of symbol \( y \) can be separated. In this paper, we only consider the real part for simplicity.

\(^2\)STAC also applies with other modulations such as QPSK, QAM, OOK, OFDM, etc. This paper only considers the simplest BPSK due to the reason mentioned in Footnote 1.

\(^3\)With the unit power of \( d_i \) in BPSK, the transmit power \( P_i |d_i|^2 \) simply equals \( P_i \).
which, through the operation
\[
\frac{1}{2} \left( \sum_{i=1}^{K} w_i - y(l) \right),
\]
yields the summation \( \sum_{i=1}^{K} w_i s_i(l) \).

Finally, the desired digit can be constructed as
\[
\sum_{l=0}^{L-1} 2^l \sum_{i=1}^{K} w_i s_i(l) = \sum_{i=1}^{K} w_i \sum_{l=0}^{L-1} 2^l s_i(l) = \sum_{i=1}^{K} w_i s_i.
\]

### B. Signal Detection

We now present a simple signal detection scheme for removing the noise in (3) to obtain (5), and analyze its corresponding SER (Symbol Error Rate). It suffices to consider only one of the \( L \) transmissions, and hence the index \( l \) as in the last subsection will be omitted.

Specifically, view the symbol \( \sum_{i=1}^{K} w_i d_i \) in (6) as a point of a non-standard PAM (Pulse Amplitude Modulation) constellation that results from the weighted superposition of the transmit BPSK constellations and hence may have unequal distance between different adjacent constellation points. A simple detection scheme is to quantize the \( y \) in (3) to its nearest constellation point. Let \( \pi \) be a permutation on \( \{1, 2, \ldots, K\} \) such that \( w_{\pi(j_1)} \leq w_{\pi(j_2)}, \forall j_1 \leq j_2 \). We have the following theorem regarding the SER with such detection.

**Theorem 1:** The SER with the nearest point detection is upper bounded by
\[
\text{SER}_{\text{STAC}} \leq (1 - 1/2^K) \text{erfc}(1/\sqrt{2}\sigma) \tag{7}
\]
where \( \text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-t^2} dt \) is the complementary error function, \( \sigma^2 \) is the variance of the noise, and the equality in (7) holds when the distance between any two adjacent constellation points is equal to 2, e.g., when \( w_{\pi(j)} = 2^{j-1} \) or 1, \( \forall j = 1, \ldots, K \).

**Proof Sketch:** Since \( w_i \) are all real integers, the largest SER is attained when the distance between any two adjacent constellation points is 2, which includes the case of \( w_{\pi(j)} = 2^{j-1} \) or 1, \( \forall j = 1, \ldots, K \).

### C. Performance of STAC

The performance of STAC is a tradeoff among SER, energy efficiency and bandwidth efficiency, and is clearly dependent of the weight coefficients. The air computation essence of STAC and its advantage over the separate strategy can be best illustrated in the ideal case of \( w_1 = w_2 = \cdots = w_K = 1 \), where we will show that for fixed energy efficiency, STAC achieves better SER and significantly improved bandwidth efficiency.

On the other hand, to show that STAC uniformly outperforms the separate strategy, we will consider the pseudo coefficients case as mentioned in Section II, i.e., \( w_{\pi(j)} = 2^{j-1}, \forall j \). The argument here is that by applying STAC with the pseudo coefficients, one can recover the original \( K \) source digits, based on which summation with any weight coefficients can be computed. We will show that in this case, STAC achieves better energy efficiency for fixed SER and bandwidth efficiency.

1) **The Ideal Case:** Suppose \( w_1 = w_2 = \cdots = w_K = 1 \), which is the ideal case for STAC. The SER of STAC is given in Theorem 1, i.e.,
\[
\text{SER}_{\text{STAC}} = (1 - 1/2^K) \text{erfc}(1/\sqrt{2}\sigma). \tag{8}
\]
Note that in this case, the resultant receive PAM constellation has only \( K + 1 \) instead of \( 2^K \), points, where the decrease of the constellation size is due to the “air computation”. Or equivalently, viewed from the energy perspective, this advantage is reflected by the fact that the needed transmit power now attains the minimum \( P_t = 1/h_i^2 \) for each node \( i \).

For the separate strategy, assume each node \( i \) transmits with the same power \( P_t = 1/h_i^2 \) as in STAC. The SER for node \( i \) is a standard result, given by \( \frac{1}{2} \text{erfc}(1/\sqrt{2}\sigma) \). Combining all the detected \( K \) symbols, the receiver computes \( \sum_{i=1}^{K} w_i d_i \), and the resultant SER \( \text{SER}_{\text{SEP}} \) is characterized in the following theorem.

**Theorem 2:** The SER with the separate strategy is given by
\[
\text{SER}_{\text{SEP}} = \frac{1}{2} - \frac{1}{2} \left( 1 - \text{erfc}(1/\sqrt{2}\sigma) \right)^K.
\]

**Proof Sketch:** The theorem can be proved by noting that the number of erroneous symbols is a binomial random variable with parameters \( (K, p) \), and the computation result is wrong if and only if there are odd number of erroneous symbols.

**Theorem 3:** \( \text{SER}_{\text{SEP}} > \text{SER}_{\text{STAC}} \) for any \( K \geq 2 \).

**Proof Sketch:** Use mathematical induction. Therefore, STAC achieves a better SER and simultaneously improves the bandwidth efficiency by a factor of \( K \). Especially, note that as \( K \to \infty \), \( \text{SER}_{\text{STAC}} \to \text{erfc}(1/\sqrt{2}\sigma) \) whereas \( \text{SER}_{\text{SEP}} \to 1/2! \) Fig. 4 plots \( \text{SER}_{\text{STAC}} \) and \( \text{SER}_{\text{SEP}} \) for \( K = 4 \).

2) **Pseudo Coefficients Case:** Consider a set of pseudo coefficients \( w_{\pi(j)} = 2^{j-1}, \forall j \). To minimize the total transmit power \( \sum_{i=1}^{K} (w_i/h_i^2) \) with STAC, we allocate these coefficients among the \( K \) nodes such that \( h_{\pi(j_1)} \geq h_{\pi(j_2)}, \forall j_1 \leq j_2 \).
Assuming STAC is completed within unit time, the total transmit energy \( E_{\text{STAC}} \) is given by

\[
E_{\text{STAC}} = \sum_{j=1}^{K} \left( \frac{2^{(j-1)}}{h_{\pi(j)}} \right)^2. \tag{8}
\]

We now calculate the total energy needed \( E_{\text{sep}} \) for the separate strategy assuming that each node transmits 1 bit to the receiver within 1/\( K \) time to maintain the same bandwidth efficiency as STAC. For the separate strategy to achieve the similar SER as STAC, the distance between any adjacent receive constellation points also needs to be 2, in which case node \( i \)'s transmit power is given by

\[
P_i = \sum_{j=1}^{K} \left( \frac{2^{(j-1)}}{h_i} \right)^2.
\]

Therefore, the total energy needed is

\[
E_{\text{sep}} = \frac{1}{K} \sum_{i=1}^{K} \sum_{j=1}^{K} \left( \frac{2^{(j-1)}}{h_i} \right)^2 \tag{9}
\]

where the factor \( 1/K \) accounts for the transmission time of each node.

Theorem 4: \( E_{\text{sep}} \geq E_{\text{STAC}} \), where the equality holds only when \( h_i \) are the same for all \( i \).

Proof Sketch: The proof utilizes the important fact that for all \( j \):

\[
w_{\pi(j_1)} \leq w_{\pi(j_2)} \text{ and } h_{\pi(j_1)} \geq h_{\pi(j_2)}, \forall j_1 \leq j_2.
\]

From Theorem 4, it can be concluded that STAC performs uniformly better than the separate strategy for any set of weight coefficients. This is because even requiring STAC to fully recover the original \( K \) source digits leads to better energy efficiency than the separate strategy, for fixed SER and bandwidth efficiency.

3) Discussion: The above analyzes two extreme cases of the weight coefficients. In general, depending on the specific weight coefficients, one has the freedom of dividing the \( K \) nodes into \( M \) groups (1 \( \leq \) \( M \) \( \leq \) \( K \)), and letting each group transmit using STAC separately, to achieve a tradeoff between the bandwidth efficiency and energy efficiency.

Now, it should be clear that our STAC scheme includes both the separate P2P transmissions and the simultaneous transmission combined with multi-user detection as special cases: Choosing \( M = K \) and viewing the P2P transmission as a degraded STAC lead to the former, while the latter is simply equivalent to applying STAC to the pseudo coefficients case.

Fig. 5 plots the normalized transmit energy per node of STAC and the separate P2P transmissions, where the channel coefficients \( h \) are assumed to be randomly generated under the standard Rayleigh distribution. It can be seen that as the number of sources \( K \) increases, the normalized transmit energy of STAC remains roughly the same for the ideal case, and increases exponentially for the pseudo coefficients case. Compared to the separate P2P transmissions, STAC can save about 95% energy when \( K > 15 \) even in the pseudo coefficients case.

V. Conclusion

The wireless DCN differs from general wireless networks in that it has large amounts of M2O sessions, which are normally followed by further computations at the destinations, with weighted summation being the typical case. Building on this observation and several distinguishing characteristics of DCs like limited and controlled physical space with static channels, we have proposed a novel physical layer scheme STAC that achieves simultaneous transmissions and computations over the air, and an enhanced SDN architecture to enable it. We showed that STAC can significantly improve both bandwidth and energy efficiencies.

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