MIComp: 3D On-chip Magneto-Inductive Computing with Simultaneous Wireless Information and Power Transfer

Burhan Gulbahar
Ozyegin University
Nisantepe Mah., Cekmekoy, 34794 Istanbul, Turkey
burhan.gulbahar@ozyegin.edu.tr

Gorkem Memisoglu
Escuela de Ingenieria de Bilbao (UPV/EHU)
Plaza Ingeniero Torres Quevedo 1, 48013, Bilbao, Spain
gorkem.memisoglu@ieee.org

ABSTRACT

On-chip computing platforms have bottlenecks including cost and physical limits of scaling transistors, communication bottleneck, energy efficiency and speed costs for memory. Three dimensional (3D) design, carbon nanotube materials, memristor based neuromorphic computing, and optical, RF and magneto-inductive (MI) wireless communication solutions are recently proposed. MI channels are non-radiative and non-interfering by forming coupled networks. They are future promising with capabilities of THz frequency, Tbit/s data rate, hundreds of zJ/bit and 10^9 W/mm^2 communication and power transfer (PT) efficiencies, respectively. In addition, recently introduced network topology modulation (NTM) for MI channels provides network communication with low complexity, low latency and simultaneous wireless information and power transfer (SWIPT). In this article, unique advantages of THz MI channels, NTM design, nanoscale materials including graphene and single molecular magnets (SMMs), and 3D design are combined in a novel on-chip computing architecture denoted by MIComp by introducing fully efficient SWIPT for computing purposes. The system is theoretically modeled while the state space of the system obtained with nanoscale size coils and SMMs achieves 10^{10} to 10^{16} bits in each cycle and per mm^3 volume of chip compared with the current transistor counts of on the orders of 10^9 per mm^2. Furthermore, each MIComp cycle has ability to perform for multiple purposes consisting of computing operations, memory state implementations and on-chip communications. It promises a novel solution for communication, energy and space bottlenecks for on-chip computing design.

CCS CONCEPTS

• **Hardware → Spintronics and magnetic technologies**; **3D integrated circuits**; **Radio frequency and wireless interconnect**; • **Networks → Network on chip**;

KEYWORDS

Magneto-inductive computing, 3D on-chip communications, simultaneous wireless information and power transfer

1 INTRODUCTION

On-chip computing platforms have important bottlenecks for next generation system design such as the difficulty of scaling silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) due to fabrication cost and fundamental physical limits, communication bottleneck for data-intensive applications, energy and speed costs for data movements between memory and processor units [5, 11, 12]. Various systems are suggested as some of the alternative platforms such as three dimensional (3D) integration of resistive random-access memory (RRAM) and carbon-nanotube field-effect transistors (CNFETs) in [11], memristors for neuromorphic and analog computing architectures in [12], and more methods for communication bottleneck such as attojoule optoelectronics in [9], and magnetic induction or magneto-inductive (MI) wireless channels with high capacity and THz frequency in [5] for on-chip communication and computing platforms. On the other hand, optical and RF solutions for on-chip interconnection have radiative nature with challenging interference problems. The recent improvements with MI channels in [5] promise a different perspective for exploiting the non-radiative magnetic fields for computing purposes while utilizing the latest advancements in nanotechnological system design with all-graphene and 3D stacked architectures.

MI wireless communication methods are recently improved for various high performance applications in both nanoscale and macroscale dimensions [1, 4, 5]. Low complexity and energy efficient communication protocols for Internet-of-things (IoT) and theoretical modeling of significant performance obtained with two dimensional (2D) materials for on-chip and in-body applications are promising novel designs exploiting the unique properties of MI channels in combination with the advancements in 2D materials [1, 5]. Unique advantages of MI designs recently introduced include THz operation frequencies, Tbit/s communication rates, hundreds of zJ/bit wireless communications, 10^9 W/mm^2 wireless power transfer (PT) and 3D layered architecture in [5]. In addition, network topology modulation (NTM) for MI channels recently introduced in [1] promises low complexity, energy efficient and fully efficient simultaneous information and power transfer (SWIPT) for multiple access channel (MAC) networks. The proposed system achieves data communication by only PT without creating any complexity for data communication. An intuitive approach is to exploit massive number of coils for a computing platform achieving computation by utilizing the logical state space of the family of the massive number of NTM symbols.

In this article, unique advantages of NTM modulation method, THz MI channels, SWIPT and nanoscale size magnetic units including coils and single molecular magnets (SMMs) are combined for a novel on-chip computing platform denoted by *MIComp*. The

theoretical model for the logical state of the computing system is provided by calculating the maximum number of bits supported by NTM. The advantages of MIComp are discussed such as SWIPT based system design with NTM, 3D design, graphene material features such as atomic thickness, planar architecture and ultra-low weight, and THz resonance frequencies. The number of bits for each cycle reaches values between 10^{10} and 10^{16} with nanoscale size coils and SMMs per mm^3 chip volume by significantly outperforming current number of transistors in 2D microprocessor platforms reaching to the orders of 10^9 per mm^2 dimensions [10]. In addition, different tasks of computation, communication and memory related issues are combined in a single computing platform as an all-in-one solution alleviating the problems occurring due to heterogeneity of the tasks.

1.1 Contributions

The contributions achieved, for the first time, in this article are described as follows:

(1) A novel on-chip computing system design denoted by *MIComp* mapping SWIPT steps realized with high efficiency MI wireless communications channels to steps of multi-purpose tasks including computation steps, memory states and on-chip wireless communications. Therefore, MIComp cycles achieves to realize a homogeneous all-in-one system architecture as a promising solution for the bottlenecks in current system architectures with the problems among memory, computation and communications tasks.

(2) Proposed architecture denoted by MIComp achieves to realize state space dimension of 10^{16} bits per cycle and per mm^3 volume compared with the state of the art transistor counts on the orders of 10^9 per mm^2 dimensions [10].

(3) SWIPT and NTM method for MI channels are for the first time utilized for on-chip computing platforms as a form energy flow, and significantly energy efficient system design.

1.2 Organization

The remainder of the paper is organized as follows. Section 2 provides a brief summary of the background topics including MI networks, NTM, SMMs and SWIPT. In Section 3, chip design and the basics of NTM are presented. In Sections 4 and 5, MIComp computing system basics are introduced and the advantages are discussed, respectively. Then, in Section 6, the proposed method is numerically simulated for finding the computation capability with various coil and chip sizes. Finally, in Sections 7 and 8, open issues and conclusions are discussed, respectively.

2 BACKGROUND

MI channels are promising for high performance wireless communications in short range robust to challenges in RF communications such as fading, dynamical effects of channels, medium dependent attenuation and interference effects due to radiative nature [5, 7]. In this article, MI channels are exploited for computing purposes based on the recent theoretical developments defining THz communications in [5], novel modulation methods proposing a novel system design allowing multiple users to communicate with low latency, low hardware complexity, security and energy harvesting
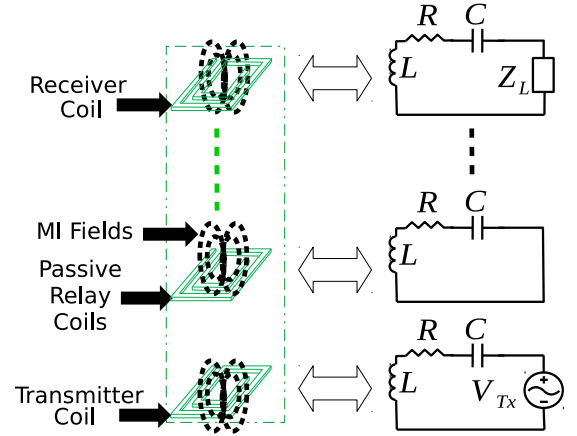

Figure 1: MI waveguide with transmitter, receiver and passive relay coils with the circuit theoretical equivalent RLC circuits where Z_L and V_{Tx} denote receiver load and transmitter voltage source, respectively.

capability in [1, 4] and utilization of SMMs for nanoscale energy harvesting and communications in [6]. Next, the background topics summarizing fundamentals of MI communications and power transfer are discussed.

2.1 MI Communications and Power Transfer

MI wireless communication channels utilize transceiver coils to modulate local magnetic fields and create induction currents on the receiver coils based on Faraday's law of induction [7] as shown in Fig. 1. Transmitter coil is resonated with the voltage source V_{Tx} while the receiver coil loaded with the impedance Z_L receives either the data or power. Each coil is assumed to have simple series RLC circuit while this can be extended to more advanced circuit structures. The simple system requires capacitive circuits resonating at the desired frequency while utilizing various materials for constructing coils such as copper or multi-layer graphene [5]. On the other hand, the induced current in the receiver coil is utilized for energy harvesting or wireless PT purposes [4]. MI communications systems do not have high latency while solving the challenges due to dynamical channel conditions requiring high power consumptions by utilizing low cost coil transceivers. They can be utilized reliably in air, seawater and various soil and rock medium having similar permeability values [7]. On the other hand, MI waveguides utilizing coupled and capacitively loaded passive coils improve the communication and PT ranges significantly [4, 7]. In this article, fundamental properties of coil based MI communications is preserved while recent methods to harvest energy in nanoscale by using SMMs are also included for computing purposes as discussed next.

2.2 Single Molecule Magnets

SMMs have large orbital moment and magnetic stability while exhibiting quantum phenomena at low temperatures [6]. They are utilized to harvest energy and to create carrier signals for MI
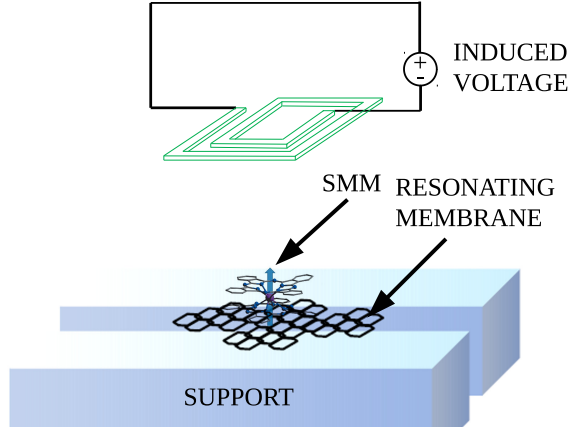
Figure 2: SMM grafted on oscillating membrane creates alternating currents on the receiver coil for energy harvesting or carrier generation purposes [6].
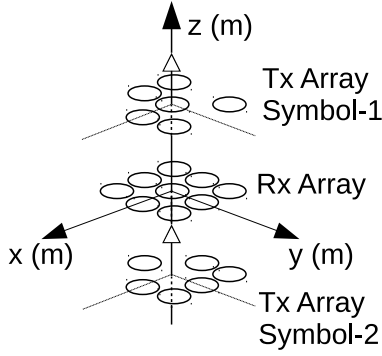

Figure 3: NTM method defined in [1] achieves to detect different sets of spatial distribution of coils in the overall network topology. Two different transmitter (Tx) coil distribution symbols are detected by receiver (Rx) coil array.

communications with a geometrical structure including resonating membranes, e.g., graphene, and SMMs grafted on the membrane as shown in Fig. 2. Resonating magnetic fields create alternating currents in the receiver coil. SMMs are future promising with applications such as molecular spintronic devices, high density information storage and quantum computation architectures. Their nanoscale properties combined with the recent advances in nanoscale 2D materials including graphene promise high density device architectures for computing purposes. On the other hand, an optimized system design is necessary to utilize SMMs with mechanical oscillation properties in MIComp system design including their interaction and the oscillation force such as optical, acoustic or molecular forces as discussed in [6].

2.3 Network Topology Modulation and SWIPT

Network topology modulation method is introduced in [1] as a novel system design improving the efficiency of multi-user networks with significant decrease in latency due to channel sharing,
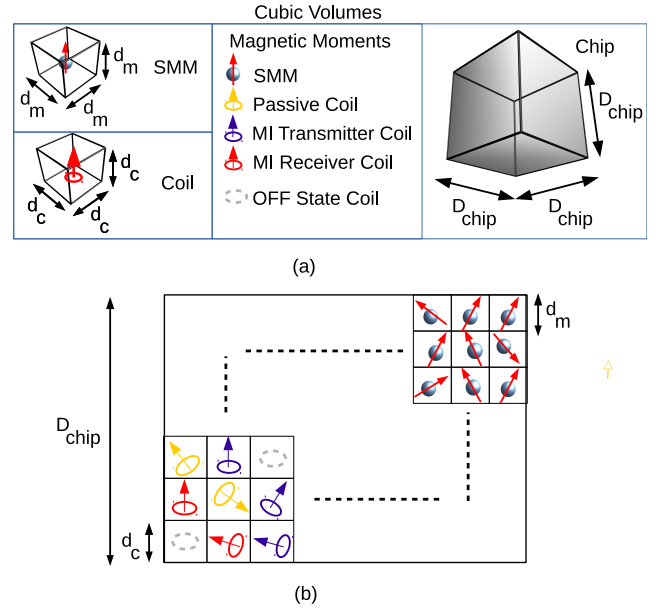

(a)

(b)

Figure 4: (a) The dimensions of the coils, SMMs and the chip are modeled as cubic volumes with side lengths of d_c, d_m and D_{chip}, respectively, while the symbols utilized for coils and SMMs are shown including their magnetic moment orientations. The coil is in one of the states as being a passive coil, receiver, transmitter or OFF state coil (without any current). In (b), 2D model of a sample topology or NTM state of the network is illustrated where the coils in each unit volume are in various states and orientations, and SMMs are in different orientations.

hardware complexity and MI properties promising advanced security. In Fig. 3, two different spatial symbols of transmitter coils are detected by the receiver coil array. Information is transmitted by changing coil positions and modulating the frequency selective MI channel instead of signal waveform modulation. NTM does not require signal modulation while not consuming power for data transmission modulation such as in some architectures for SWIPT separating data and power transmission signals as discussed in detail in [1]. SWIPT is a novel mechanism exploiting data transmission for energy harvesting purposes or transmitting data and power to remote sources simultaneously. NTM achieves to couple information and power transfer in a fully efficient manner as an advanced form of SWIPT. Next generation IoT device requirements are satisfied including low hardware complexity, low latency, security capabilities, supporting complicated network communications with massive number of users and energy harvesting with SWIPT. In this article, NTM methodology is combined with nanoscale coils and SMMs for compact and high density computing architecture.

3 SYSTEM MODEL

The proposed on-chip architecture is composed of nanoscale coils and molecular magnets as shown in Fig. 4(a) where unit cubic

volumes of coils, SMMs and the chip are shown with the definitions of the symbols used for SMMs, passive, receiver, transmitter and OFF state coils. N different coils and M molecular magnets are placed in 3D on-chip medium with pre-designed positions $\vec{x}_j = (x_j, y_j, z_j)$ and unit magnitude moment orientation vector $\vec{n}_j = \begin{bmatrix} n_{x,j} & n_{y,j} & n_{z,j} \end{bmatrix}^T$ for $j \in [1, N + M]$. Each coil performs either as a transmitter, receiver or relay as discussed in previous architectures with detailed models for circuit theoretical equivalents, MAC networks and NTM applications provided in [1, 4]. Each coil has series RLC type circuit with the same resistance R, capacitance C and inductance L for simplicity where operating frequencies include simultaneous oscillation at the frequency levels (or a subset) of $S_f = f_k, k \in [1, N_f]$. Voltage levels ($\mathbf{V}_f$) and coil currents ($\mathbf{I}_f$) in the network are coupled by the following equation:

$$\mathbf{V}_f = \mathbf{M}_f \, \mathbf{I}_f \qquad (1)$$

where $\mathbf{M}_f$ is $N \times N$ mutual inductance matrix where the corresponding column and row values are zero for a coil not operating, i.e., in OFF state. It has $\mathbf{M}_f(i, j) = \jmath\, 2\pi f\, M(i, j)$ for $i \neq j$, $Z_i + Z_L$ for $i = j \in [1, N_R]$ and Z_i for $i = j \in [N_R + 1, N]$ where N_R is the number of receiver coils, Z_L is the load impedance in the receivers, $Z_i = R + \jmath \omega L + 1/(\jmath \omega C)$, $\jmath = \sqrt{-1}$ is the complex unity and $M(i, j) = M(j, i)$ is the mutual inductance between ith and jth coils [1]. Assume that the coils are indexed with k for $k \in (1, N_R)$ as receivers, $k \in (N_R + 1, N_R + N_{re})$ as relays, $k \in (N_R + N_{re} + 1, N_R + N_{re} + N_{OFF})$ as OFF-state coils, and $k \in (N - N_T + 1, N_T)$ as transmitters where $N = N_T + N_{re} + N_R + N_{OFF}$. Then, $\mathbf{V}_f^T = \begin{bmatrix} 0 & \dots & 0 & V_1 & V_2 & \dots & V_{N_T} \end{bmatrix}$ is the transmitter voltage sources in the network and $\{.\}^T$ is transpose operation.

The dimensions of the coils, SMMs and the chip are modeled as occupying cubic volumes with side lengths of d_c, d_m and D_{chip}, respectively. Then, the total number of coils and molecular magnets are found as follows:

$$N = \left(\frac{D_{chip}}{d_c}\right)^3; \quad M = \left(\frac{D_{chip}}{d_m}\right)^3; \qquad (2)$$

where it is assumed that a coil and and a SMM are inside the same chip volume allowing significantly small distance between each other while coils or SMMs among their own types are only allowed to occupy d_c^3 and d_m^3 cubic volumes with a single coil or SMM, respectively.

The set of concurrently active coils forms a specific topology creating a unique distribution of currents in the receiver coils [1]. In Fig. 4(b), an illustration of a single topology of the network or NTM state is shown where molecular magnets are utilized as voltage generating blocks in the network by providing additional degrees of freedom, smaller size and higher spatial complexity for modulating the magnetic field distribution in the on-chip channel. The coils are in one of the states performing as either passive coil, receiver (energy harvesting), transmitter or OFF-state coil without any current or effect on the network [4].

A non-contact electro-mechanical THz source for inducing currents in the transmitter coils as energy resource or for harvesting energy in receiver coils is suggested in [5]. One of the best candidates to achieve the purpose is to utilize single molecular magnets with high magnetic moments [3]. A candidate with Terbium(III)

bis(phthalocyanine) (TbPc$_2$) SMMs is discussed in [3] for the application of spintronic devices in a device combined with graphene resonators. In this article, the design of resonator structures to harvest energy from single SMMs is left as an open issue. It is assumed that each SMM has the ability to change the orientation and to be oscillated at the desired frequency. Therefore, energy generating SMMs with oscillating states modifies the magnetic field in the medium and can be used as building blocks similar to transmitter coils. Geometrical 3D design issues are discussed next.

4 MAGNETO-INDUCTIVE COMPUTING

Each computing operation is performed by creating a specific state of the network by assigning specific states to the receivers, and orienting coils and SMMs to the desired orientation for the duration of the cycle. If the angular orientations are not taken into account, then N coils have 2^N different combinations of ON-OFF states at a cycle period of T_c. The number is increasing exponentially producing a high computation logical set space. The proposed system promises significantly large number of degrees of freedom by using nanoscale coils and molecular magnets in a manner comparable with transistor sizes. On the other hand, it harvests energy from each operation by realizing SWIPT. Each operation cycle lasts a duration of T_c assumed as some multiple of the oscillation period T_s. As a result, a computing operation corresponds to a specific network topology where energy flows in the network with the minimum amount of loss optimized by tuning the network properties.

MI systems allow significant amount of efficiency in power transfer by exploiting THz frequency, waveguides (or a specific group of passive coils) and high performance coil structures with novel materials such as graphene [1, 4, 5]. If the power loss in each flow is minimized and a much larger logic state space is realized by using NTM methodology, then energy lasts for a long duration in the chip compared with the irreversible consumption of energy in traditional computing architectures such as in transistor capacitances, leakage currents, resistive circuit elements, interfaces between memory and the processor. Memory can be implemented as a consecutive set of energy flow operations in the network by creating different topologies similar to implementing logic operations. The mapping of ordinary logic and memory operations to the specific set of NTM symbols is an open issue. On the other hand, the difficulties in interconnect technologies experienced with current wired and wireless architectures are not experienced in the proposed architecture by naturally including SWIPT as a form of fundamental communication method and energy flow as shown in Fig. 5. Required set of computation operations, memory states and communication steps are mapped to a chain of NTM symbols in a sense routing the energy in the network for optimization of energy energy efficiency in the network. MIComp not only proposes an alternative design for interconnect bottleneck in on-chip platforms but also proposes a combination of different tasks of computation, memory and communication in a single NTM step.

The number of logical states denoted by S_c for fixed coil orientations is given by the following formulation:

$$S_c = \sum_{i=2}^{N-1} \binom{N}{i} \left(\sum_{j=1}^{i-1} \binom{i}{j} 2^{i-j} \right) \qquad (3)$$
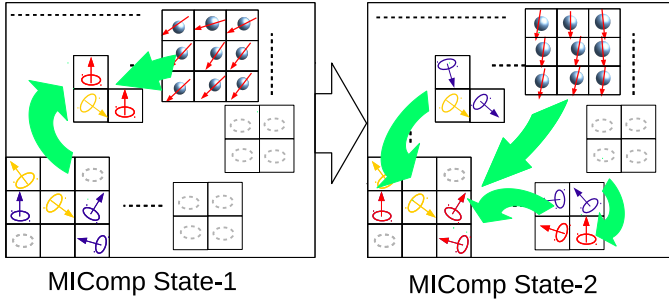
Figure 5: A consecutive set of states where energy flows in the 3D network topology to the receiver coils.
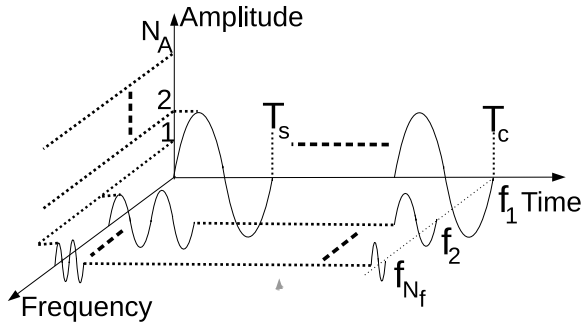

Figure 6: A transmitter coil resonates at a set of frequencies f_k $k \in [1, N_f]$ for a cycle duration of $T_c > T_s$ where the amplitude is at a set of N_A distinct values.

where $\binom{a}{b}$ denotes the possible number of combinations for choosing b elements from the set of a elements, the term $\binom{N}{i}$ is the number of topologically distinct set of coils which are currently active (similar to ON-OFF states of transistors in classical digital computing architectures) and $\left(\sum_{j=1}^{i-1} \binom{i}{j} 2^{i-j} \right)$ is counting the number of different ways of choosing the receiver coil set and grouping the remaining $i - j$ coils as either transmitters or passive relays. In addition to the degrees of freedom obtained with NTM, the number of discrete oscillation frequencies, amplitudes and coil orientations denoted by N_f, N_A, and N_ϕ, respectively, modulate magnetic field distribution in the network resulting in different coil currents in frequency and amplitude domains in the current set of receivers. The transmitter coils operate at N_f different frequencies with amplitude values at a set of N_A distinct values as shown in Fig. 6. Therefore, the receiver coils are resonated with pure sinusoids at a set of distinct frequencies while harvesting energy for the duration of T_c which is assumed as some multiple of the oscillation period T_s. Including the angular orientations of moments, (3) is converted to the following:

$$S_c^{tot} = \sum_{i=2}^{N-1} (N_\phi N_A)^i \left(\binom{N}{i} \left(\sum_{j=1}^{i-1} \binom{i}{j} 2^{i-j} \right) \right) \qquad (4)$$

where the measurement of coil currents at multiple frequencies increases the number of logical states linearly. If $N, N_{phi}, N_{tot} \gg 1$, then the number of logical sets is dominated approximately by the

term for $i = N - 1$ and the result becomes larger than approximately $(N_\phi N_A)^{N-1} (N - 1) 2^{N-1}$. Including angular orientations of the molecular magnets brings significant improvement on the number of logical states. The capability to collectively orient the oscillating magnetic moment of molecular magnets enhances the number of logical states. Assuming that there are M different molecular magnets with fixed moments and positions while oscillating periodically and generating a periodic magnetic field modulation similar to coils. The number of total logical states including different orientations of SMMs denoted by $S_{c,mol}^{tot}$ is computed as follows:

$$S_{c,mol}^{tot} = S_c^{tot} N_\phi^M \qquad (5)$$

where N_ϕ denotes the degrees of freedom in angular directions of the magnetic moments for each molecule. Then, the maximum number of bits at a state is defined as $N_{bit} \equiv \log_2 S_{c,mol}^{tot}$ being approximately on the order of $\log_2 \left((N_\phi N_A)^{N-1} (N - 1) 2^{N-1} N_\phi^M \right)$ which becomes as follows:

$$N_{bit} \approx O\left((N - 1) \times \beta_c + \beta_N + N - 1 + M \beta_m \right) \qquad (6)$$

where $\beta_c = \log_2(N_\phi N_A)$, $\beta_N = \log_2(N - 1)$ and $\beta_m = log_2 N_\phi$. The number of bits is improved significantly with nanoscale dimensions of magnets. In addition, magnets perform as direct energy harvesters for the receiver coils while the resource for oscillation requires external excitation for magnets, i.e., external magnetic fields at the desired oscillation frequency sets with the size N_f or other methods such as optical and acoustic methods [6].

The total received power at a single frequency f_j for $j \in [1, N_f]$ for a computation step realized with a topology matrix $\mathbf{M}_{i,f_j}$ indexed by $i \in [1, S_{mol}^{tot}]$ is given by $P_R(i, f_j) = \sum_{k=1}^{N_R} |\mathbf{I}_{i,f_j}(k)|^2 Z_L$ where $\mathbf{I}_{i,f_j}(k)$ is the kth element of the vector $\mathbf{I}_{f_j} = \mathbf{M}_{i,f_j}^{-1} \mathbf{V}_{i,f_j}$ and Z_L is predefined load impedance where energy is harvested. Then, for N_f different set of simultaneous oscillations, the total received power is given as follows:

$$P_{R,Tot}(i) = \sum_{k=1}^{N_R} \sum_{j=1}^{N_f} |\mathbf{I}_{i,f_j}(k)|^2 Z_L \qquad (7)$$

while the consumed power is $P_{T,Tot}(i) = \sum_{j=1}^{N_f} \mathbf{V}_{i,f_j}^T \mathbf{I}_{i,f_j}$. As a result, each operation has an efficiency of $E(i) \equiv P_{R,Tot}(i)/P_{T,Tot}(i) < 1$ given as follows:

$$E(i) = \frac{\sum_{k=1}^{N_R} \sum_{j=1}^{N_f} |\mathbf{1}_k \mathbf{M}_{i,f_j}^{-1} \mathbf{V}_{i,f_j}|^2 Z_L}{\sum_{j=1}^{N_f} \mathbf{V}_{i,f_j}^T \mathbf{I}_{i,f_j}} \qquad (8)$$

where $\mathbf{1}_k$ is the vector of all zeros except kth element being equal to one. $E(i)$ is required to be optimized with respect to the design of the specific MIComp processor. The processing operations decrease and increase power levels of specific sets of coils requiring an optimization for the best SWIPT based computing operations. Energy flow optimization is an open issue for MIComp system design. On the other hand, specification of each unique topology is tuned with geometrical and circuit theoretical design of coils, frequency of operation, the numbers of coils and magnets, transmit power and other system parameters.

5 MI COMPUTING ADVANTAGES

Recent studies utilizing MI wireless methods with multi-layer graphene coils promise THz operation frequencies, several Tbit/s communication rates, ultra-low power (500 zJ/bit) wireless communications, high (hundreds of kWs) and efficient (10^9 W/mm^2) on-chip communication and power transfer capability [5]. Therefore, combined in a computing platform, MI systems perform as a significant alternative compared with RF or optical interconnection based systems. Although spatial modulation and SWIPT are recently analyzed in detail for RF systems [2, 8], it is highly challenging to realize fully coupled system design with RF systems to be utilized for communication and computing purposes and for exploiting network information theoretical advantages similar to NTM. In the following sections, main advantages and features are discussed in detail.

5.1 Computing with SWIPT

The capability to transfer energy among the coils in the network improves energy efficiency significantly since energy is saved in each ith operation cycle with efficiency of E_i. Each logical operation or communication step is now transformed to a form of high efficiency energy transfer between coils. If high mutual inductance is realized among the massive set of nodes, then high values of E_i are generated depending on the efficiency of the couplings. Energy consumptions are reduced by combining SWIPT with NTM method and by exploiting high efficiency MI couplings. Optimization of the topology design and mapping of operations on specific set of NTM symbols in a way maximizing the efficiency of requested set of computations, minimizing energy consumption and improving processing speed are open issues.

5.2 THz Operation Frequency

THz frequency operation of MI wireless channels is recently modeled theoretically in [5] by utilizing multi-layer graphene coils with micrometer dimensions. Higher frequency operation improves the range and increases the number of fully connected nodes resulting in larger symbol family, higher number of bit operations and better PT efficiency at each NTM step.

5.3 2D Material Coils and Molecular Magnets

Coils with 2D materials such as graphene allow nanoscale size units significantly large number of nodes to be placed in a compact volume in a 3D layered design with a fully coupled architecture. Resistive elements and the decrease in the coupling performance due to smaller dimensions should be optimized with respect to the desired specifications. Graphene has atomic thickness, ultra-low weight and the resonance frequencies reaching THz both electronically and mechanically allowing magneto-mechanical designs as an open issue. On the other hand, SMMs with high magnetic moments allow high performance nanoscale NTM design with both energy harvesting and high density of fully coupled nodes [3]. The optimization of the number of SMMs, their resonator structures and theoretical modeling of energy harvesting are discussed in detail in [6] and the details of the analysis is left as a future work.

6 NUMERICAL SIMULATIONS

The total number of bits (N_{bit}) is simulated numerically for varying coil, SMM and chip volumes. It is assumed that high performance capabilities of MI networks proposed previously combining graphene and THz operation frequencies are experimentally verified. Therefore, the proposed number of coils is assumed to be in the fully coupled regime. In [5], several millimeter ranges are theoretically achieved with 1 μW transmission power for coil-to-coil coupling with dimensions of $d_c \in [5\,\mu m, 15\,\mu m]$. The detailed analysis for computing the number of distinct NTM symbols which could be demodulated efficiently is an open issue.

In Fig. 7(a), the number of bits is simulated for the design including both coils and SMMs for varying cubic volume side lengths of d_c, d_m and D_{chip} for the coil, SMM and chip, respectively while $N_\phi = N_A = 64$ is utilized allowing the coils and SMMs to modulate magnetic moment direction. It is observed that the maximum number of bits reaches to the orders of 10^{19} for coil or SMM volume side lengths of on the orders of tens of nanometer and D_{chip} on the orders of millimeters comparable with the current state of the art. The promised number of bits by the simulated MIComp architecture is much larger than the number of transistors in currently realized microprocessors. It requires either the mass production of nanoscale size coils or the placement of high magnetic moment SMMs to the chip volume in a controllable fashion. The improvements in the nanoscale capabilities both for graphene and SMM promise the feasibility of the proposed design. On the other hand, SMM occupying larger volume per unit, i.e., 1 μm^3, provides N_{bit} on the orders of $= 10^{10}$ independent from the coil size as a significant performance.

In Fig. 7(b), a more simplified architecture is simulated by using only the coils while also fixing their orientations ($N_\phi = 1$) and voltage oscillation levels in transmission ($N_A = 1$). $D_{chip} = 1$ mm is chosen for simplicity. It is observed that the capabilities to realize nanoscale coils and to place them in a full coupled manner allowing NTM symbols to be demodulated distinctly result in N_{bit} reaching 10^{16} as a significant computation performance.

7 OPEN ISSUES AND CHALLENGES

There are various open issues and challenges to optimize the system design and to experimentally realize the prototype described as follows:

- Mass manufacturing of nanoscale sized coils should be performed with low cost solutions. The simplicity of the coil circuit and the structure is significantly promising mass production to be realized with the current systems which have the capabilities for producing much more complicated transistor structures.
- 3D integration methods for massive amounts of coils and SMMs should be developed for low cost integration system design.
- The number of distinctly demodulated NTM symbols for given transmit power, coil, SMM and chip dimensions should be theoretically modeled. System design for coils and SMMs should be optimized to achieve the bounds proposed in this article.
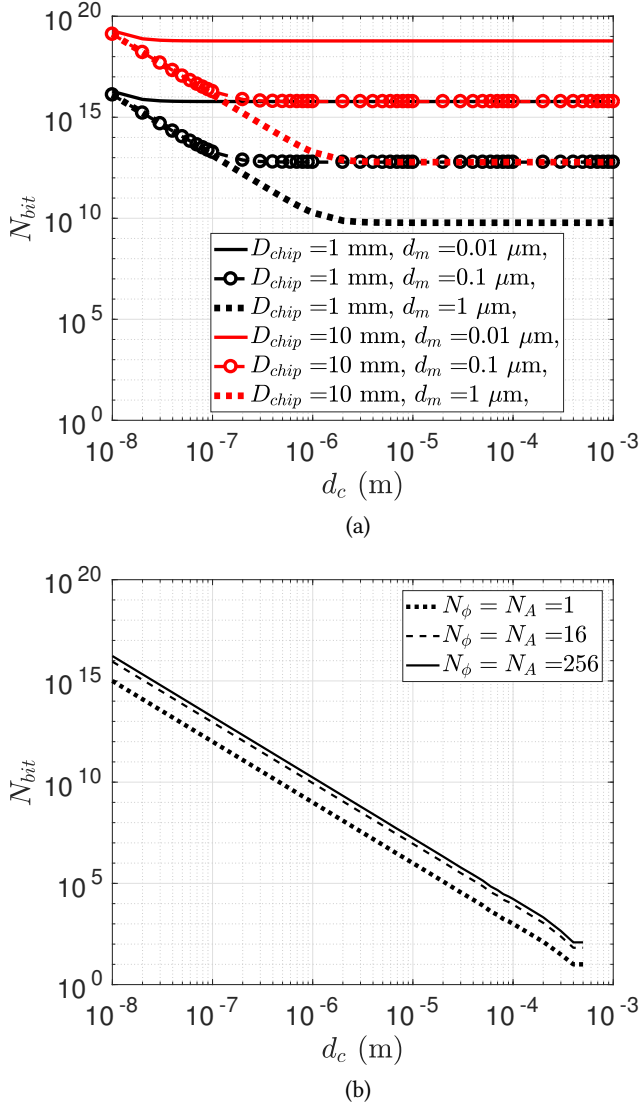
(a)

(b)

Figure 7: (a) N_{bit} for varying cubic volume side lengths of d_c, d_m and D_{chip} for the coil, SMM and chip, respectively, where $N_\phi = N_A = 64$, and (b) N_{bit} for varying d_c and $N_\phi = N_A$ while without any SMM placements and $D_{chip} = 1$ (mm).

- Mapping of computation, memory and communication tasks to NTM steps should be defined and optimized for low energy and fast operation of tasks.
- Energy efficiency of the whole system should be theoretically modeled by clarifying performance metric in terms of joule/bit such that the advantages of SWIPT as a form of energy flow should be calculated.
- Resistive structure of the nanoscale coils and the decrease in the mutual coupling should be optimized with respect to the desired computing specifications. On the other hand, SMMs promise nanoscale harvesting units with high volumetric

density of the units and excitation by external mechanical, optical or acoustic methods for next generation IoT microprocessors [6]. The design of resonator structures to utilize SMMs in the system should be described.

8 CONCLUSIONS

A novel on-chip computing platform denoted by *MIComp* is introduced and theoretically modeled by exploiting MI wireless communication channels, SWIPT, recently introduced NTM method, THz communication frequencies and unique properties of graphene. Each cycle in the proposed computing platform achieves to realize state space dimension of 10^{16} bits per mm^3 volume with nanoscale coil and SMM dimensions. MIComp achieves to realize an all-in-one system design for multiple tasks of computation, memory state representation and on-chip wireless communications. It offers a promising solution for the bottlenecks in next generation on-chip systems due to problems of memory, computation and communications tasks, and physical limits of scaling transistors with costly operations.

REFERENCES

[1] B. Gulbahar. 2016. Network topology modulation for energy and data transmission in Internet of magneto-inductive things. *IEEE Globecom Workshops (GC Wkshps)* (2016), 1–6.
[2] Suzhi Bi, Chin Keong Ho, and Rui Zhang. 2015. Wireless powered communication: Opportunities and challenges. *IEEE Communications Magazine* 53, 4 (2015), 117–125.
[3] Andrea Candini, Svetlana Klyatskaya, Mario Ruben, Wolfgang Wernsdorfer, and Marco Affronte. 2011. Graphene spintronic devices with molecular nanomagnets. *Nano letters* 11, 7 (2011), 2634–2639.
[4] Burhan Gulbahar. 2017. A communication theoretical analysis of multiple-access channel capacity in magneto-inductive wireless networks. *IEEE Transactions on Communications* 65, 6 (2017), 2594–2607.
[5] Burhan Gulbahar. 2017. Theoretical analysis of magneto-inductive THz wireless communications and power transfer with multi-layer graphene nano-coils. *IEEE Transactions on Molecular, Biological and Multi-Scale Communications* 3, 1 (2017), 60–70.
[6] B. Gulbahar. 2018. Theoretical Modeling of KHz to THz Simultaneous Energy Harvesting and Magneto-Inductive Communications with Molecular Magnets on Vibrating Graphene. *to appear in IEEE Transactions on Molecular, Biological, and Multi-Scale Communications* (2018).
[7] Burhan Gulbahar and Ozgur B Akan. 2012. A communication theoretical modeling and analysis of underwater magneto-inductive wireless channels. *IEEE Transactions on Wireless Communications* 11, 9 (2012), 3326–3334.
[8] Chaowen Liu, Lie-Liang Yang, and Wenjie Wang. 2017. Transmitter Precoding Aided Spatial Modulation Achieving Both Transmit and Receive Diversity. *IEEE Transactions on Vehicular Technology* 67, 2 (2017), 1375–1388.
[9] David AB Miller. 2017. Attojoule optoelectronics for low-energy information processing and communications. *Journal of Lightwave Technology* 35, 3 (2017), 346–396.
[10] Dharmendra S Modha. 2017. Introducing a brain-inspired computer. *Published online at http://www. research. ibm. com/articles/brain-chip. shtml* (2017).
[11] Max M Shulaker, Gage Hills, Rebecca S Park, Roger T Howe, Krishna Saraswat, H-S Philip Wong, and Subhasish Mitra. 2017. Three-dimensional integration of nanotechnologies for computing and data storage on a single chip. *Nature* 547, 7661 (2017), 74.
[12] Mohammed A Zidan, John Paul Strachan, and Wei D Lu. 2018. The future of electronics based on memristive systems. *Nature Electronics* 1, 1 (2018), 22.