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Enhancing Energy Efficiency in Wireless Sensor Networks Using Virtual MIMO Technology

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Abstract

This study investigates utilizing Virtual Multiple Input Multiple Outputs (MIMO) methodologies to boost energy efficiency in wireless sensor network communication. It proposes an innovative approach to routing that capitalizes on virtual MIMO technology, scrutinizing its effectiveness across consistent and adaptable transmission rates. By employing a cluster-based virtual MIMO framework, this study aims to adjust operational variables to enhance communication energy efficiency significantly. The research prioritizes optimizing routing paths, specifically tailoring them to minimize the virtual MIMO communication cost. This strategic focus aims to extend the operational lifespan of the network's initial node, delaying its energy depletion. Through comprehensive simulation analyses, findings reveal that the virtual MIMO-based routing strategy significantly surpasses the energy efficiency of traditional Single Input Single Output (SISO) approaches and various other MIMO configurations, especially notable when managing communications over extended distances. This advancement holds promising implications for developing more sustainable and efficient wireless sensor networks.

Keywords *Wireless Network, Virtual MIMO, Space-time block code, Diversity Data rate*

Introduction

Virtual Multiple-Input Multiple-Output (MIMO) technology has garnered significant attention within networking due to its potential for enhanced energy efficiency (Jayaweera, 2004). The core concept involves a group of sensors that collaboratively transmit and receive data, forming a virtual MIMO network (Sachan et al., 2018a). This cooperative approach enables long-range communications with the significant benefit of reduced energy consumption (Xiao & Xiao, 2004). However, a key consideration is that increasing the number of transmitters and receivers within the network also leads to a corresponding increase in circuitry power consumption (Bravos & Kanatas, 2005; Yuan et al., 2006). Consequently, according to Tarokh et al. (1999), optimizing energy utilization requires techniques that are adaptable to specific environmental conditions. Due to the complexities associated with integrating separate antennae, virtual MIMO principles are proving invaluable in wireless sensor networks (WSNs). By applying these concepts, WSNs can realize energy-efficient communication while simultaneously boosting reliability (Blum et al., 2001). Moreover, Cooperative virtual Multiple-Input Multiple-Output (MIMO) technology can significantly enhance the energy efficiency of wireless communications by facilitating the shared transmission and reception of information (Bhavitha et al., 2018). Within a virtual MIMO framework, multiple senders and receivers collaborate to achieve long-range communication, bolstering data reliability even in fading channels (Brar et al., 2016). It is important to note that the performance of virtual MIMO systems implemented within wireless sensor networks (WSNs) is intrinsically linked to both the network layer and data link layer structures (Kumar et al., 2017; Malleswari & Rao, 2013; Nake & Chatur, 2016). Researchers have explored several distinct approaches for implementing virtual antenna arrays within WSNs (Chen, 2016; Duraichi & Suganthi, 2017; Sachan et al., 2018a). A cluster-based virtual MIMO model offers the flexibility to dynamically adjust operational parameters, allowing the system to be precisely tailored to meet specific design requirements (Zhang et al., 2018). This adaptability is essential for optimizing energy consumption, data transmission rates, and overall network performance.

This research follows a structured organization to present the research findings effectively. It begins with a comprehensive review of related work in the field, establishing the research context and highlighting the areas where this study makes a distinct contribution. The article then delves into the core of the research by detailing the proposed network model and offering a thorough analysis of its total energy consumption. Subsequently, the focus shifts to the simulation process and the presentation of results, meticulously outlining the simulation environment, parameters, and evaluation methodology. The results of the key performance metrics are discussed, offering insights into the model's strengths, potential limitations, and performance relative to existing approaches. Finally, the paper concludes by summarizing the main findings and their implications, while also suggesting promising avenues for future research and potential refinements of the current work.

Literature Review

In wireless sensor networks (WSNs), exploring Multiple Input Multiple Outputs (MIMO) technologies, particularly those based on the Alamouti diversity scheme, significantly enhances network efficiency and performance (Halgamuge et al., 2009; Yao & Giannakis, 2005). These methodologies extend to the cooperative engagement of individual single-antenna array nodes, which collectively function as multi-antenna transmitters or receivers, fostering a notable improvement in energy conservation during the transmission and reception of information. According to recent studies (Anees & Zhang, 2022; Padmavathy & Chitra, 2010; Suryawanshi, 2016), MIMO systems demonstrate superior performance over Single Input Single Output (SISO) configurations beyond certain communication distances, emphasizing the critical role of optimal array size in leveraging long-distance communication advantages (Cedeno et al., 2019). This cooperative transmission approach facilitates substantial energy savings and paves the way for innovative routing and link scheduling strategies at the network layer, contributing to improved end-to-end performance and reduced energy consumption. Further investigation into MIMO technologies for WSNs highlights the potential of virtual MIMO to mimic the efficiency of physical MIMO systems, especially under conditions of low signal-to-noise ratios (Nowshin et al., 2020). Adopting virtual MIMO, characterized by its strategic management of power allocation and timing, offers a viable solution for enhancing the network's energy efficiency without necessitating local information exchange among nodes (Boursianis et al., 2021). This approach underlines the capacity of virtual MIMO to achieve comparable levels of performance to its physical counterparts, making it a promising avenue for research and development in the field (Jayaweera, 2006). Moreover, integrating multiple layers for cooperative transmission within the virtual MIMO framework underscores this technology's multifaceted benefits, including optimizing energy utilization and extending network lifespan.

The synergistic effect of combining MIMO with cooperative transmission techniques and advanced network layer strategies presents a comprehensive method for addressing energy consumption challenges and communication efficiency in WSNs. As evidenced by empirical studies, implementing [2×2] MIMO configurations for long-distance communication to base stations without local information exchange signifies a substantial leap forward in network design (Yuan et al., 2006). By focusing on the optimal allocation of time and power resources, research in this area continues to unveil the transformative potential of MIMO technologies in reducing energy consumption and enhancing overall network performance. The cumulative findings of these studies not only validate the superiority of MIMO over traditional SISO systems in long-distance scenarios but also spotlight the innovative applications of virtual MIMO in achieving unprecedented energy savings and efficiency in wireless sensor networks. The exploration of energy-efficient communication strategies in wireless sensor networks (WSNs) has led to the adoption of virtual Multiple Input Multiple Outputs (MIMO) technologies, specifically focusing on optimizing node clusters and transmission strategies to enhance energy conservation. Studies have underscored the importance of determining the optimal number of nodes within a cluster and the configuration of transmission points to maximize energy savings in virtual MIMO communication systems (Asif et al., 2017; Samara & Hosseini, 2017). Furthermore, incorporating training overhead and orthogonal Space-Time Block Coding (STBC) into MIMO architectures emerge as a critical component for facilitating accurate channel estimation and effectively leveraging multiple antennas. This dual focus on structural optimization and advanced coding techniques is instrumental in refining the virtual MIMO approach, ensuring that it supports robust and energy-efficient communication across WSNs (Boursianis et al., 2021).

An in-depth analysis of these virtual MIMO systems reveals the strategic advantage of utilizing a consistent group of nodes as transmitters and receivers in a relay configuration. This methodological choice is pivotal for enhancing the efficiency of data transmission processes, thereby minimizing energy expenditure and extending the operational lifespan of the network. Research indicates that the synergy between optimized cluster formation and the deployment of orthogonal STBC significantly improves the network's resistance to signal degradation and interference, thereby bolstering the reliability and quality of communication (Tarokh et al., 1999). Moreover, such strategies effectively reduce energy consumption and achieve higher data rates and improved coverage, thereby addressing the multifaceted demands of modern WSN applications. The increasing body of research on virtual MIMO in WSNs highlights the transformative potential of these technologies in overcoming traditional barriers to efficient and reliable communication. By prioritizing the optimization of node clustering, transmission point configuration, and the implementation of advanced coding mechanisms, virtual MIMO systems offer a promising avenue toward achieving unprecedented levels of energy efficiency. This holistic approach to network design and operation, characterized by meticulous structural and procedural optimization, underscores the critical role of virtual MIMO technologies in setting new benchmarks for performance and sustainability in wireless communication networks (Gai et al., 2007). As such, advancements in this field continue to pave the way for developing more resilient, efficient, and scalable WSN infrastructures capable of accommodating the evolving demands of digital communication landscapes.

Proposed Model and Solution

In the realm of wireless sensor networks (WSNs), the incorporation of virtual Multiple Input Multiple Output (MIMO) systems presents a revolutionary step forward from the traditional Single Input Single Output (SISO) paradigm, vastly enhancing the efficiency of energy utilization in long-distance transmissions. The complexity of integrating multiple physical antennas on miniature sensor nodes due to spatial and circuit constraints necessitates the adoption of virtual MIMO configurations that emulate the benefits of actual MIMO systems (Goldsmith, 2005). The schematic presented in Figure 1 exemplifies a network where a sender node exploits multiple transmitters to convey messages to a destination node through intermediary receivers, showcasing a shift from singular to collective transmission and reception processes. This strategic multiplicity not only provides diversity gains through techniques like Space-Time Block Coding (STBC) but also invokes a careful balancing act between diversity and multiplexing, thereby optimizing the data transmission rate and robustness of communication links (Anees et al., 2020; Cheour et al., 2017). The decision matrix for the appropriate transmission mode—whether it be MIMO, SIMO (Single Input Multiple Output), MISO (Multiple Input Single Output), or retaining SISO—becomes a function of variable determinants such as transmission distance, data rate, and the number of transmitters and receivers engaged in the communication process (Sachan et al., 2018b). Within this framework, the bit rate of transmitters, denoted as bits per symbol, is pivotal in dictating the data transmission rate for each link within the network. By coordinating the operations across various network layers, virtual MIMO systems not only streamline energy expenditure but also consolidate data throughput, transcending conventional transmission modes' limitations. The collective optimization across layers is central to maximizing energy savings, which is critical for the sustainability and extended operational capacity of WSNs (Blum et al., 2001; Nakamura et al., 2007). As the WSNs evolve, the fusion of virtual MIMO systems with sophisticated coding and signal processing techniques emerges as a cornerstone for future advancements in wireless communication, promising to augment sensor networks' reliability, efficiency, and scalability in an increasingly connected world (Anees et al., 2020; Xiao & Xiao, 2004).

Figure 1: Virtual MIMO example

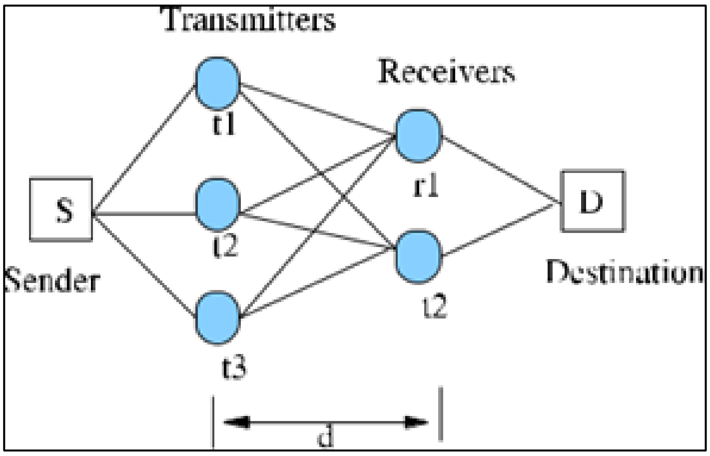
Due to space limitations and circuit complexity. This study assumes network is synchronized. For MIMO communication, this study uses STBC coding for diversity with a tradeoff between diversity and multiplexing. Based on the number of transmitters and receivers, this study may get the following combinations: MIMO (multiple multiple output), SIMO (single input, multiple output), MISO (multiple input, single output), and SISO (single in- put single output) (Fineberg et al., 2013; Yamsanwar & Sutar, 2017). Further, depending on the transmission distance, data rate, and number of transmitters and receivers, the appropriate mode of transmission, MIMO, SIMO, MISO, or SISO would be determined (Cedeno et al., 2019; Yamsanwar & Sutar, 2017). The transmitters' bit rate, b, is defined as bits per symbol. As a result, each link will have its data transmission rate. The cooperation of each layer optimizes the energy savings for virtual MIMO communication.

It is provided as:

$$b = \frac{L}{BT_{\text{on}}} = \frac{R_b}{B} \quad (1)$$

Where:

- b is the bit rate (bits per symbol),
- L is the packet size in bits,
- B is the bandwidth (Hz),



- T_{on} is the time duration the transmitter is on (seconds),
- R_b is the data rate (bits/second).

In WSNs, the sensor node has a low-duty cycle, and the node is often off to conserve energy. The energy consumption is computed by adding the on, sleep, and transient states, as given below.

$$E = P_{\text{on}} \times T_{\text{on}} + P_{\text{sleep}} \times T_{\text{sleep}} + P_{\text{transient}} \times T_{\text{trans}}$$

The energy consumption model for a sensor node in a Wireless Sensor Network (WSN) can be refined to account for the active and transient states, excluding the sleep state, as follows:

$$E = (P_{\text{transmit}}(1+\alpha) + P_{\text{circuit}}) \times T_{\text{on}} + 2P_{\text{syn}} \times T_{\text{transient}}$$

Here, P_{transmit} is the power consumed during transmission, α represents the amplification factor related to the power amplifier efficiency (where $\alpha=\eta-1$), and P_{circuit} represents the power consumed by the sensor node's circuitry. The power consumed by the synthesizer during transient states is approximately twice the power ($2P_{\text{syn}}$). This yields an energy consumption equation for active and transient states:

$$E = (P_{\text{transmit}}(1+\alpha) + P_{\text{C}}) \times T_{\text{on}}$$

The transmit power P_{Transmit} is derived from the average energy consumption per bit (Ea), the data rate (Rb), and other factors such as the distance and the link path loss:

$$P_{\text{Transmit}} = \frac{E_b R_b \times (4\pi)^2 d_{ij} k_{ij}}{t_r M_t N_r}$$

Finally, the average energy consumption per bit (Ea) can be calculated by summing the contributions of all the transmitters and receivers in the network, adjusted for the distance and path loss between each transmitter-receiver pair ($d_{ij}k_{ij}$), and normalizing it by the bit rate and bandwidth. The total circuit power consumption (P_C) is the sum of the transmitter and receiver circuit power consumptions, multiplied by the number of transmitters (N_T) and receivers (N_R), respectively:

$$E_a = \zeta \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} (d_{ij} k_{ij}) + \frac{P_C}{bB}$$

In this context, ζ serves as a constant of proportionality, d_{ij} and k_{ij} are distance and path loss coefficients, b represents bits per symbol, and B represents the bandwidth. This model provides an intricate view of the energy dynamics in WSNs, which is essential for optimizing energy consumption and extending the network's lifespan.

In the literature, uniform path loss factors have been traditionally used when analyzing the power requirements for multiple transmitters and receivers in a network (Jayaweera, 2006; Samara & Hosseini, 2017). The current approach deviates from this by incorporating distinct path loss factors for each transmitter-receiver pair, which allows for the calculation of individualized transmit power levels corresponding to the unique path loss experienced on each link (Cedeno et al., 2019; Gai et al., 2007; Guo et al., 2019). Contrasting with studies that examine multiple transmitter systems with uniform path loss under fixed rate systems (Boursianis et al., 2021), this methodology extends the analysis to variable rate systems, accommodating unique path loss factors for a diverse set of transmitters and receivers. The model in question suggests that reducing the average energy consumption per bit is feasible by either increasing the bits per symbol, which involves expanding the constellation size or by decreasing the distance between communicating nodes, which potentially reduces or stabilizes the path loss (Sinha & Lobiyal, 2013; Yamsanwar & Sutar, 2017). However, it is critical to recognize that while the latter strategy is quite straightforward, enlarging the constellation size is not without its challenges (Cedeno et al., 2019; Singh et al., 2019). As spectral efficiency goes up with a larger constellation size, so does the energy required for transmission.

Strategic placement of transmitters and receivers can substantially affect the distances between nodes and, consequently, the energy efficiency of the network. Yet, there are practical limits to increasing the constellation size because it is proportionally linked to the energy consumed during transmission (Guo et al., 2019). Determining the optimal constellation size thus becomes a complex task that must be carefully calibrated to the specific transmission distances, recognizing the non-linear complexities of this optimization challenge (Sinha & Lobiyal, 2013). These considerations form an integral part of the design calculus for wireless sensor networks, where the imperatives of energy conservation, communication range, and data throughput must be carefully balanced.

Virtual MIMO node selection

In a cluster, some nodes are selected as transmitter and receiver nodes. The same node can be chosen as both transmitter and receiver (Samara & Hosseini, 2017). The cluster head (CH) selects the appropriate transmitter and receiver nodes to minimize the distance between transmitters and receivers. The proposed virtual MIMO framework has four types of nodes: normal nodes, transmitter nodes, receiver nodes, and

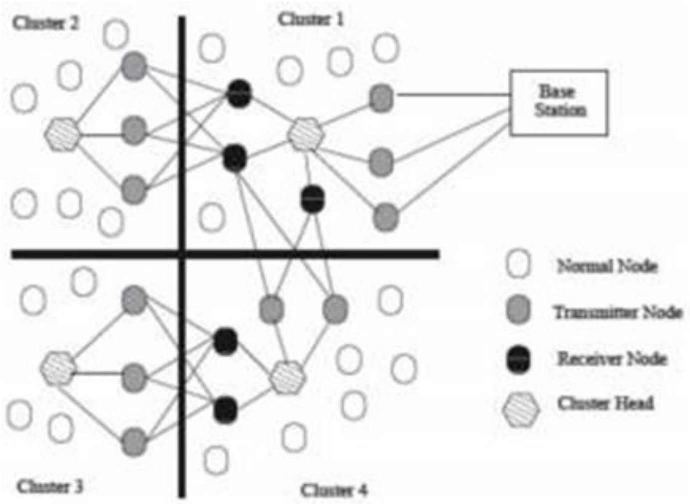


Figure 2: Virtual MIMO network

cluster heads. The normal nodes sense and collect data regarding the environment (Jayaweera, 2006). The Cluster head (CHs) collects data from the normal nodes and uses transmitter nodes to transmit their data to the receiver nodes of the neighboring cluster or send data directly to the base station. All the nodes in the

cluster will transmit data to the CH.

procedure MIMO “ RoutingPath(List)

```
/* List contains all the cluster heads
*/
while List != 0 do
    CHmin ← Extract Min(List)
    Estimate MIMO Energy(CHmin)
    CHmin(T) ← (t1 . . . tn)
    CHmin(R) ← (r1 . . . rm)
End while
```

Energy consumption analysis

The analysis of energy consumption in Wireless Sensor Networks (WSNs) encompasses both transmission energy and the energy consumed by the electronics within the sensor nodes (Marinho et al., 2016). The total energy expenditure for transmitting and receiving a single bit can be bifurcated into the analog and digital components of the node's circuitry. The overall energy consumed per bit (E_b) is the sum of the energy consumed by the transmission process (E_{trans}) and the energy consumed by the circuitry (E_{circ}):

$$E_b = E_{trans} + E_{circ}$$

The energy associated with the transmission (E_{trans}) is dependent on the transmission power and the time the node is active (T_{on}), normalized by the number of bits (L) transmitted:

$$E_{trans} = (\alpha + 1) \cdot P_t \cdot \frac{T_{on}}{L}$$

Where:

α is the amplifier efficiency factor,
P_t is the transmit power,
T_{on} is the duration of transmitting L bits.

The energy consumed by the node's circuitry ($Ecirc$) involves the power dissipation of various components within the node during the transmission of L bits and the energy consumed during the state transition (Ttr):

$$E_{circ} = \left(P_{c\_ana} + P_{detector} + P_{c\_dig}\right) \cdot T_{on} + 2 \cdot P_{syn} \cdot T_{tr}$$

Where:

- P_{c_ana} is the power dissipated by the analog circuitry,
- $P_{detector}$ is the power dissipated by the detector,
- P_{c_dig} is the power dissipated by the digital circuitry,
- P_{syn} is the power dissipated by the frequency synthesizer,
- T_{tr} is the time required for the node to transition from 'sleep' to 'awake' mode.

Now, the importance of the power dissipated on the circuitry on the total performance of the MIMO system, which depicts the total energy consumption for MIMO 2x2 and SISO architectures versus the distance of the long transmission, based on the parameters shown in

Table 1: Power Dissipation Parameters

Parameter	Value	Units
Bits per Packet (L)	1000	bits
Frequency (f)	2500	MHz
P_filters	7	mW
P_syn	25	mW
P_ADC	7	mW
P_mix	4.7	mW
P_LNA	7.2	mW
P_IF	3	mW
T_tr	5	µs
P_detector	5	mW
n	2	
P_c_dig	1	mW

Result Analysis

Figure 3 clearly compares the energy consumption patterns of Single Input, Single Output (SISO), and Multiple Input Multiple Output (MIMO) architectures across various communication distances. The graph indicates that the non-transmission power-related energy consumption, mainly associated with circuit components like filters and mixers, is the predominant energy-consuming factor in MIMO systems. This suggests that with the rapid advancements in micro-electronic efficiency, MIMO architectures stand to benefit significantly, potentially reducing their overall energy usage as more efficient circuitry becomes available. On the other hand, the SISO architecture's total energy consumption is more heavily influenced by the transmission power (E_{trans}), which becomes increasingly prominent with longer distances. The current trend points towards a future where the efficiency gains in electronic circuitry are expected to lower the energy consumption of MIMO systems to the extent that they could surpass SISO systems in energy efficiency across a broad spectrum of operational scenarios. This potential shift could render MIMO architectures more favorable for various applications, especially those involving longer-distance communication where energy efficiency is paramount.

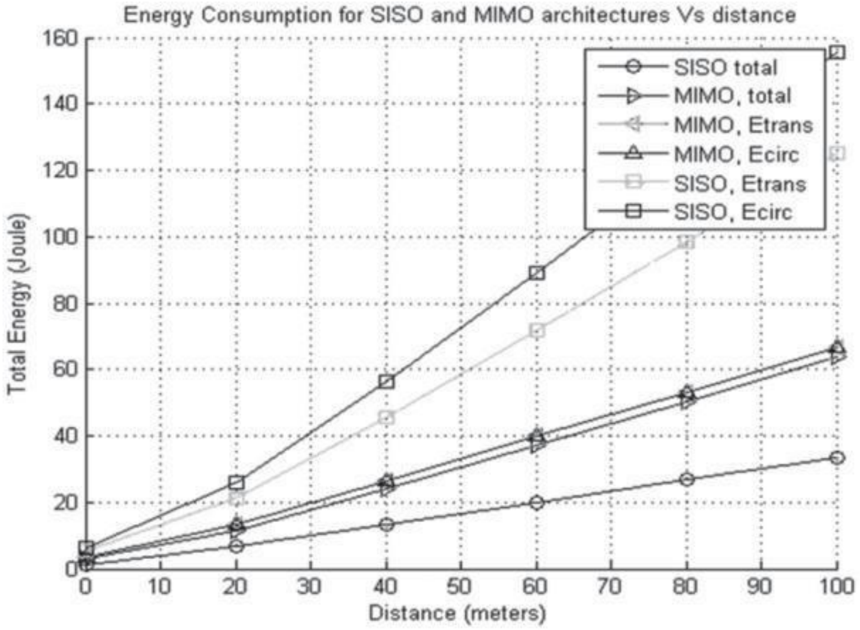


Figure 3:Energy Consumption for SISO and MIMO Architectures Vs Distance

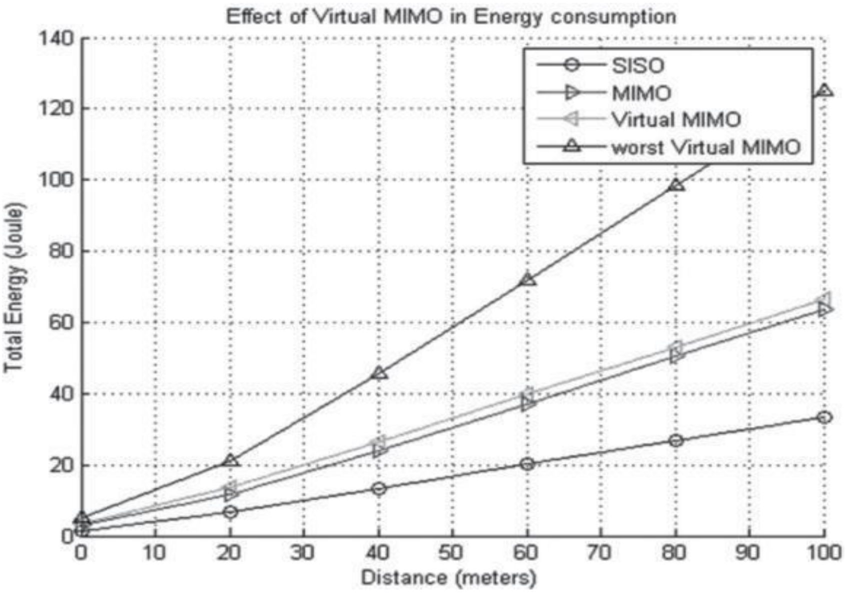


Figure 4: Effect of Virtual MIMO on Energy Consumption

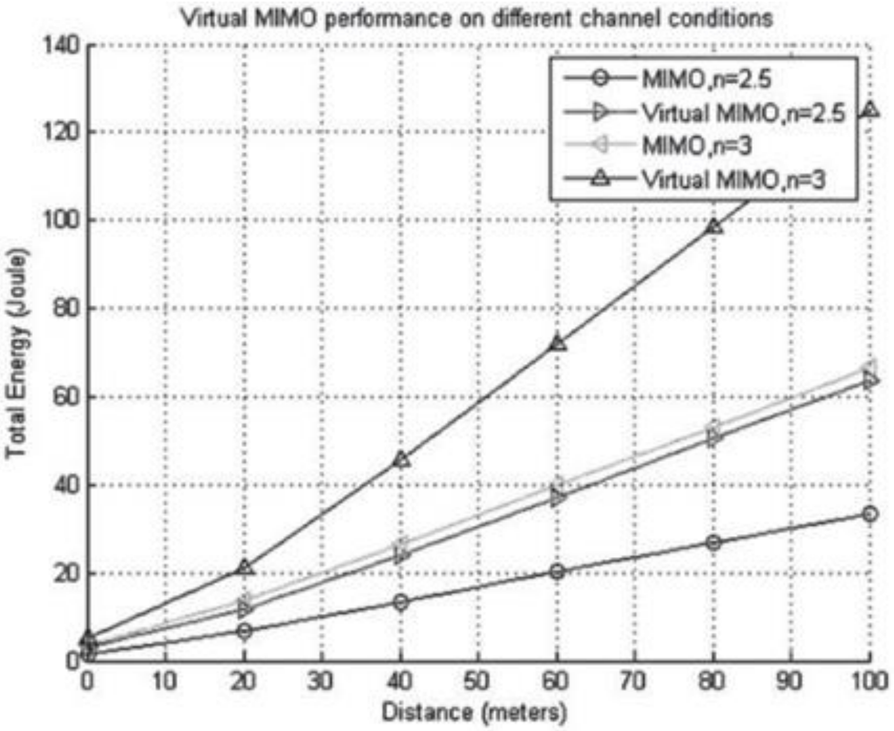


Figure 5: Virtual MIMO Performance on Different Channel Conditions

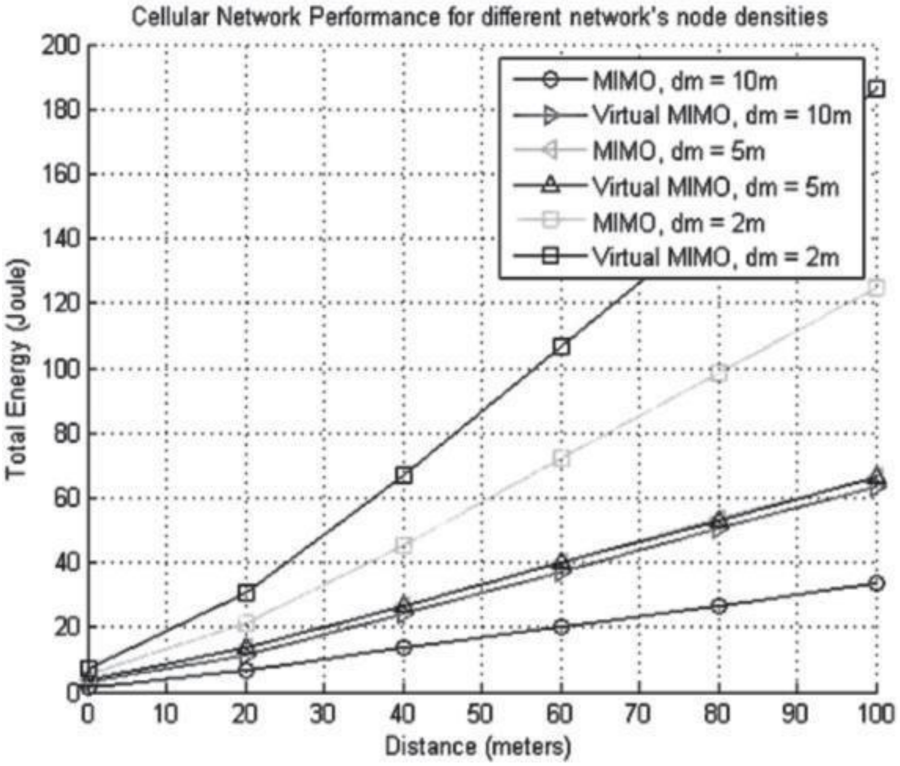


Figure 6: Virtual MIMO Performance for Different Network's Node Densities

In the analysis portrayed by the figure, scenarios with larger values of D_M, representing lower network density, are scrutinized, revealing that when D_M is less than 1 meter, its impact on total energy consumption is considered negligible. However, as D_M increases, there is a corresponding uptick in total energy consumption; this is attributed to the heightened transmission power required to maintain connectivity across the expanded distances between nodes. Despite this, the application of Virtual MIMO technology appears to be resilient to these changes, consistently delivering substantial improvements in energy efficiency. The figure further allows exploration into various scenarios characterized by different node density values, indicated by the variable dm, which signifies the average inter-node distance. This variable serves as a key determinant of network density, directly influencing the overall energy dynamics of the system.

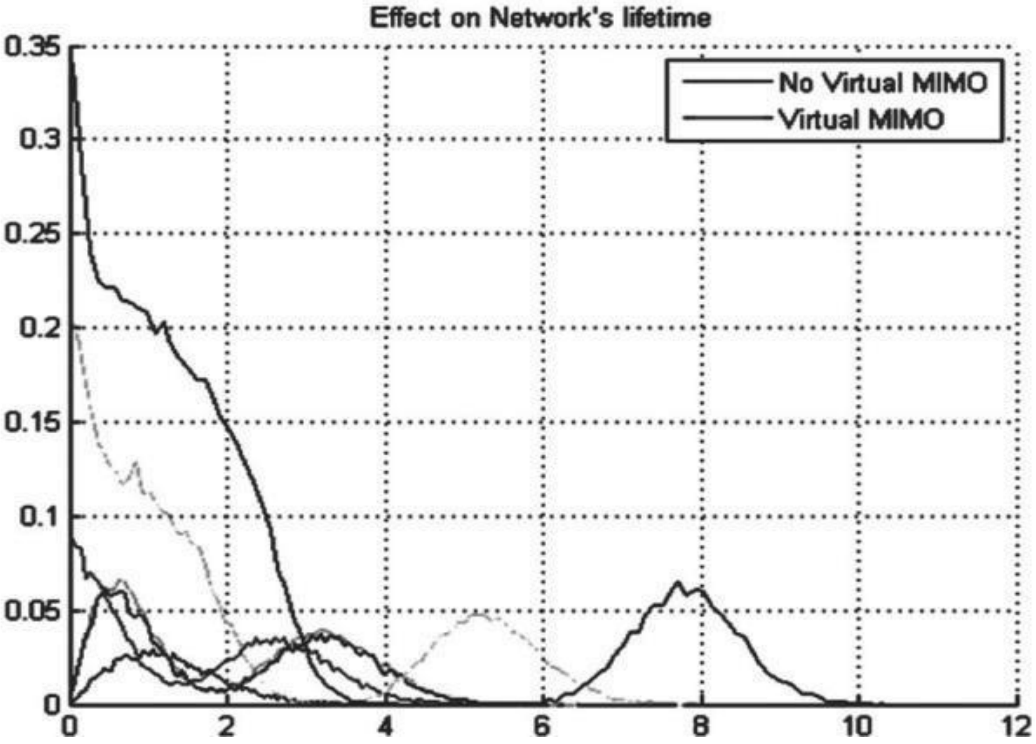


Figure 7: Effect on Network's Lifetime

Conclusion

The swift advancements in micro-electronics technology have set the stage for Multiple Input Multiple Output (MIMO) structures to eclipse the traditional Single Input Single Output (SISO) schemes in terms of energy efficiency and overall performance. The trajectory of these technological developments suggests that soon, MIMO configurations will become the standard for wireless communication, largely due to their superior capacity for managing energy consumption and their ability to maintain robust communication links over various distances. This progression aligns with the underlying goal of wireless networks to achieve optimal operational efficiency without compromising quality or connectivity. The anticipated dominance of MIMO structures is predicated on their inherent design, which allows for the strategic distribution of energy usage across multiple transmission and reception points, thereby enhancing the network's longevity and reliability.

Implementing Virtual MIMO is particularly promising, as it is strategically designed to minimize energy consumption by carefully selecting neighboring nodes to compose a virtual multiple-input antenna array. This scheme is aligned with energy-saving imperatives and simplifies the deployment process by requiring minimal hardware or software modifications. Integrating Virtual MIMO into existing network infrastructures offers a cost-effective path to harness additional energy savings while bolstering network resilience. Such a scheme is poised to deliver significant benefits, particularly in dense network environments where energy resources are a premium. Consequently, as Virtual MIMO technology matures, it stands to offer a transformative impact on the landscape of wireless sensor networks, driving them towards unprecedented levels of efficiency and effectiveness.

References

Anees, J., & Zhang, H.-C. (2022). FLOC: Hesitant Fuzzy Linguistic Term Set Analysis in Energy Harvesting Opportunistic Clustering Using Relative Thermal Entropy and RF Energy Transfer. *International journal of Computer Networks & Communications*, *14*(2), 19-39. https://doi.org/10.5121/ijcnc.2022.14202

Anees, J., Zhang, H.-C., Baig, S., Lougou, B. G., & Bona, T. G. R. (2020). Hesitant Fuzzy Entropy-Based Opportunistic Clustering and Data Fusion Algorithm for Heterogeneous Wireless Sensor Networks. *Sensors (Basel, Switzerland)*, *20*(3), 913-NA. https://doi.org/10.3390/s20030913

Asif, M., Khan, S., Ahmad, R., Sohail, M., & Singh, D. (2017). Quality of Service of Routing Protocols in Wireless Sensor Networks: A Review. *IEEE Access*, *5*(NA), 1846-1871. https://doi.org/10.1109/access.2017.2654356

Bhavitha, K., Sravani, T., & Alluri, B. K. R. (2018). Energy Efficient Channel Accessing Protocol for Wireless Sensor Network. *2018 IEEE International Conference on System, Computation, Automation and Networking (ICSCA)*, *NA*(NA), NA-NA. https://doi.org/10.1109/icscan.2018.8541220

Blum, R. S., Li, Y. G., Winters, J. H., & Yan, Q. (2001). Improved space-time coding for MIMO-OFDM wireless communications. *IEEE Transactions on Communications*, *49*(11), 1873-1878. https://doi.org/10.1109/26.966049

Boursianis, A. D., Papadopoulou, M., Gotsis, A. G., Wan, S., Sarigiannidis, P., Nikolaidis, S., & Goudos, S. K. (2021). Smart Irrigation System for Precision Agriculture—The AREThOU5A IoT Platform. *IEEE Sensors Journal*, *21*(16), 17539-17547. https://doi.org/10.1109/jsen.2020.3033526

Brar, G. S., Rani, S., Chopra, V., Malhotra, R., Song, H., & Ahmed, S. H. (2016). Energy Efficient Direction-Based PDORP Routing Protocol for WSN. *IEEE Access*, *4*(NA), 3182-3194. https://doi.org/10.1109/access.2016.2576475

Bravos, G., & Kanatas, A. G. (2005). Energy consumption and trade-offs on wireless sensor networks. 2005 IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications,

Cedeno, N. Z., Asqui, O. P., & Chaw, E. E. (2019). The performance of QoS in wireless sensor networks. *2019 14th Iberian Conference on Information Systems and Technologies (CISTI)*, *NA*(NA), 1-5. https://doi.org/10.23919/cisti.2019.8760756

Chen, D.-R. (2016). An energy-efficient QoS routing for wireless sensor networks using self-stabilizing algorithm. *Ad Hoc Networks*, *37*(NA), 240-255. https://doi.org/10.1016/j.adhoc.2015.08.022

Cheour, R., Jmal, M. W., & Abid, M. (2017). Hybrid energy-efficient power management for wireless sensors networks. *2017 International Conference on Smart, Monitored and Controlled Cities (SM2C)*, *NA*(NA), 143-146. https://doi.org/10.1109/sm2c.2017.8071836

Duraichi, N., & Suganthi, M. (2017). Energy Maximization in MIMO_WSN Through Successive Convex Approximation in Cluster Nodes. *Journal of Computational and Theoretical Nanoscience*, *14*(8), 3772-3776. https://doi.org/10.1166/jctn.2017.6672

Fineberg, S. J., Nandyala, S. V., Marquez-Lara, A., Oglesby, M., Patel, A. A., & Singh, K. (2013). Incidence and risk factors for postoperative delirium after lumbar spine surgery. *Spine*, *38*(20), 1790-1796. https://doi.org/10.1097/brs.0b013e3182a0d507

Gai, Y., Zhang, L., & Shan, X. (2007). WCNC - Energy Efficiency of Cooperative MIMO with Data Aggregation in Wireless Sensor Networks. *2007 IEEE Wireless Communications and Networking Conference*, *NA*(NA), 791-796. https://doi.org/10.1109/wcnc.2007.151

Guo, H., Gao, Y., Xu, T., Zhang, X., & Ye, J. (2019). A secure and efficient three-factor multi-gateway authentication protocol for wireless sensor networks. *Ad Hoc Networks*, *95*(NA), 101965-NA. https://doi.org/10.1016/j.adhoc.2019.101965

Halgamuge, M. N., Zukerman, M., Ramamohanarao, K., & Vu, H. L. (2009). An estimation of sensor energy consumption. *Progress In Electromagnetics Research B*, *12*(12), 259-295. https://doi.org/10.2528/pierb08122303

Jayaweera, S. K. (2004). Energy analysis of MIMO techniques in wireless sensor networks. 38th conference on information sciences and systems,

Jayaweera, S. K. (2006). Virtual MIMO-based cooperative communication for energy-constrained wireless sensor networks. *IEEE Transactions on Wireless Communications*, *5*(5), 984-989. https://doi.org/10.1109/twc.2006.1633350

Kumar, K. S., Amutha, R., & Snehapiriya, T. (2017). Energy efficient V-MIMO using turbo codes in Wireless Sensor Networks. *2017 2nd International Conference on Computing and Communications Technologies (ICCCT)*, *NA*(NA), 293-298. https://doi.org/10.1109/iccct2.2017.7972288

Malleswari, P. N., & Rao, G. V. (2013). An Energy Efficient Virtual MIMO Communication for Cluster-based Wireless Sensor Networks. *International journal of engineering research and technology*, *2*(4), NA-NA. https://doi.org/NA

Marinho, M. A. M., da Costa, J. P. C. L., Antreich, F., de Freitas, E. P., & Vinel, A. (2016). *WiSEE - Adaptive communication and cooperative MIMO cluster formation for improved lifetime in wireless sensor networks* (Vol. 2016). https://doi.org/10.1109/wisee.2016.7877330

Nakamura, E. F., Loureiro, A. A. F., & Frery, A. C. (2007). Information fusion for wireless sensor networks: Methods, models, and classifications. *ACM Computing Surveys*, *39*(3), 9-NA. https://doi.org/10.1145/1267070.1267073

Nake, N. B., & Chatur, P. N. (2016). An energy efficient grid based routing in mobile sink based wireless sensor networks. *2016 Second International Conference on Science Technology Engineering and Management (ICONSTEM)*, *NA*(NA), 1-5. https://doi.org/10.1109/iconstem.2016.7560872

Nowshin, N., Mukter Hossain Emon, M., Rahat, M. K., Ashikul Islam, M., & Alam, R. (2020). Sea Water Desalination for Coastal Area Using Concentrated Sunlight and Solar Panel. Intelligent Systems and Applications: Proceedings of the 2019 Intelligent Systems Conference (IntelliSys) Volume 1,

Padmavathy, T. V., & Chitra, M. (2010). Extending the Network Lifetime of Wireless Sensor Networks Using Residual Energy Extraction—Hybrid Scheduling Algorithm. *International Journal of Communications, Network and System Sciences*, *3*(1), 98-106. https://doi.org/10.4236/ijcns.2010.31015

Sachan, A., Nigam, S., & Bajpai, A. (2018a). An energy efficient virtual-MIMO communication for cluster based cooperative wireless sensor network. 2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT),

Sachan, A., Nigam, S., & Bajpai, A. (2018b). ICCCNT - An Energy Efficient Virtual-MIMO Communication for Cluster Based Cooperative Wireless Sensor Network. *2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, *NA*(NA), 1-6. https://doi.org/10.1109/icccnt.2018.8493985

Samara, K., & Hosseini, H. (2017). Simulation Study of QoS in Wireless Sensor Networks. *2017 International Conference on Computational Science and Computational Intelligence (CSCI)*, *NA*(NA), NA-NA. https://doi.org/10.1109/csci.2017.113

Singh, R., Kumar, B., & Bose, S. K. (2019). Modeling and Performance Analysis for Pipelined-Forwarding MAC Protocols for Linear Wireless Sensor Networks. *IEEE Sensors Journal*, *19*(15), 6539-6552. https://doi.org/10.1109/jsen.2019.2910209

Sinha, A., & Lobiyal, D. K. (2013). Performance evaluation of data aggregation for cluster-based wireless sensor network. *Human-centric Computing and Information Sciences*, *3*(1), 13-NA. https://doi.org/10.1186/2192-1962-3-13

Suryawanshi, R. (2016). H-WSN with maximized QoS using secure data aggregation. *2016 2nd International Conference on Contemporary Computing and Informatics (IC3I)*, *NA*(NA), 149-154. https://doi.org/10.1109/ic3i.2016.7917950

Tarokh, V., Jafarkhani, H., & Calderbank, A. R. (1999). Space-time block codes from orthogonal designs. *IEEE Transactions on Information Theory*, *45*(5), 1456-1467. https://doi.org/10.1109/18.771146

Xiao, L., & Xiao, M. (2004). A new energy-efficient MIMO-sensor network architecture M-SENMA. IEEE 60th Vehicular Technology Conference, 2004. VTC2004-Fall. 2004,

Yamsanwar, Y., & Sutar, S. (2017). Performance analysis of wireless sensor networks for QoS. *2017 International Conference on Big Data, IoT and Data Science (BID)*, *NA*(NA), NA-NA. https://doi.org/10.1109/bid.2017.8336584

Yao, Y., & Giannakis, G. B. (2005). Energy-efficient scheduling for wireless sensor networks. *IEEE Transactions on Communications*, *53*(8), 1333-1342. https://doi.org/10.1109/tcomm.2005.852834

Yuan, Y., He, Z., & Chen, M. (2006). Virtual MIMO-based cross-layer design for wireless sensor networks. *IEEE Transactions on Vehicular Technology*, *55*(3), 856-864.

Zhang, W., Xuanren, W., Han, G., & Tan, X. (2018). An Energy-Efficient Ring Cross-Layer Optimization Algorithm for Wireless Sensor Networks. *IEEE Access*, *6*(NA), 16588-16598. https://doi.org/10.1109/access.2018.2809663