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A Software-Defined Radio-Based Adaptable Antenna System for Satellites using Internet of Remote Things

Manish Nandy[1], **Yalakala Dinesh Kumar**[2]

[1]*Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India.*

[2]*Research Scholar, Department of CS & IT, Kalinga University, Raipur, India.*

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ABSTRACT

This paper has enabled the making of high-performance adaptable antenna systems for satellite communication. These now bring forth unmatched flexibility and efficiency compared to other systems by adding the reconfigurability property of Software-Defined Radio (SDR) with that of Internet of Remote Things (IoRT) connectivity. Current satellite communication systems suffer from poor adaptability to dynamic frequency demands, resource allocation inefficiencies, and a lack of scalability. All these factors restrict effective communication in environments with variable conditions or high mobility requirements. To overcome these difficulties, this paper presents an SDR adaptable antenna system (AAS) for satellites using IoRT to augment connectivity. The architecture of SDR combines its property of dynamic reconfigurability of signal processing parameters with adaptive antenna designs that learn real-time communication needs. IoRT facilitates smooth monitoring and control of the system to ensure efficient operations across diverse scenarios. The proposed system is intended for application in satellite communication networks. It is aimed to improve the utilization of a spectral band, reduce latency, and enhance the connection in remote or hostile environments. It integrates smart algorithms that enable autonomous antenna configurations for multi-band and multi-mode operations. The results show enhanced communication efficiency and adaptability. The SDR-AAS framework outperforms the traditional methods by achieving better data rates, signal quality, and reliable performance under varying conditions. This adaptive system is a precursor to next-generation satellite communication solutions that would be flexible, scalable, and efficient in communication technology for the growing demand for such technologies.

Author's e-mail: ku.manishnandy@kalingauniversity.ac.in, yalakala.prerana.sunil@kalinga-university.ac.in

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INTRODUCTION

Satellite communications systems are crucial in modern communications infrastructure.[1] This supports the application of global positioning, weather forecasting, disaster management, and military operations, among others.[11] Since demand increases for high-speed data transfer and reliable connectivity, these traditional satellite communications face certain limitations. These include the following: One of the major disadvantages is rigidity in conventional antenna systems; these are designed based on frequencies and fixed configurations.[12] These limitations prevent the system from dynamically adapting to changes in environmental conditions, leading to inefficiencies in data transmission, reduced signal strength, and increased latency.[3] The advent of the SDR technology has brought new prospects for increasing flexibility and adaptability in the communication system [16]. SDR permits a change in protocols, frequencies, and many other parameters through software modifications rather than hardware. The flexibility it offers can greatly increase the efficiency of satellite communication systems.[4] However, despite SDR's advantages, satellite antenna systems still have inadequate adaptability in dynamic conditions, leading to nonoptimal performance in real-time operation.[5]

The Internet of Remote Things and SDR make it easier to obtain signals, improve data throughputs, and enhance overall performance in agile satellite environments, proving to be the next big advancement. Because of the IoRT & SDR, this composite enables a comparative level of performance against competition across a wide range. It enables the real-time monitoring of environmental elements, which allows for the automatic adjusting of the antennas for better outcomes, forming the basis of IoRT. Existing problems are obliterated through the integration of software-defined radios and the IoRT & the proposed adaptable antenna system, which is software-driven, is really effective in handling satellite communications and provides for better communication in a traditional framework due to the elasticity of SDR. When custom satellite communication is utilized, satellites can monitor their situations in real-time and decide the most suitable communication action, which mitigates the signal loss when switching communication standards is necessary, thus making the communications system optimal. For best performance, antenna systems can be tuned and redeployed or placed to meet different communications standards based on the user's requirement, thus allowing for delay-free communications. Software-managed satellite antennas make the impossible possible by solving real-time problems.[17]

Encapsulated in this method are the components that enhance and bolster satellite communication systems, decrease the time it takes for communications to connect, and decrease the risk of corruption of data transferred through the system. Moreover, the dynamic characteristic of this novel method allows for its use in operations that require better robustness and performance, such as responding to disasters, using it in military fields, and performing remote surveillance. With the combined attributes of SDR and IoRT, this solution bridges the gap left in satellite communications, and it looks forward to having more streamlined and versatile systems. Combining SDR and IoRT into satellite communications is a major milestone in achieving versatile and flexible systems.[8] The approach makes satellite communications more reliable, efficient and effective by eliminating dependencies dictated by traditional antenna systems and allowing real-time changes in operational settings [6]. Given the ever-increasing demand for universal interconnectivity, the suggested adaptive satellite antenna system will certainly be indispensable in realizing the goals associated with the next generation of communication systems.[2]

Problem statement: With the help of satellite communication systems, Global Positioning System, Weather forecasts, Disasters Management and even warfare activities are successfully carried out worldwide. However, the typical communication satellites encounter challenges that limit their efficiency and adaptability in fast-changing environments. Standard antenna systems are static, operating at a specific frequency and configuration without updating in real-time to changes in the external environment, such as satellite positioning and the availability of various consumers. The consequence of this is the inefficient transmission of data, low quality of signals, low bandwidth usage, and a long waiting time.

Contribution of this paper,

- The paper introduces a **Software-Defined Radio-Based Adaptable Antenna System (SDR-AAS)** that dynamically reconfigures antenna designs and signal processing to enhance satellite communication efficiency and flexibility.
- This paper proposes using the Internet of Remote Things (IoRT) to enable seamless monitoring, control, and adjustment of satellite systems, ensuring reliable, robust communication in remote, dynamic, and challenging environments.
- The proposed SDR-AAS framework addresses the limitations of traditional systems, improving data rates, signal quality, and scalability, providing a flexible and efficient solution for next-generation satellite communication networks.

Section 2 explains the related works in this paper, section 3 shows the proposed method, and section 4 explains the result and discussion. Finally, section 5 presents the conclusion of future works.

RELATED WORKS

The rapid advancement of communication technology has significantly changed how modern systems operate, especially in satellite communication (SATCOM), unmanned aerial vehicles (UAVs), and software-defined system domains. SDR has emerged as a key solution that offers flexibility, adaptability, and cost-effectiveness for developing robust communication networks. Unlike traditional hardware-dependent systems, SDRs rely on software changes to adapt different communication protocols and standards, making them suitable for applications with high levels of reconfigurability and scalability.[13] In the SATCOM and the related fields, SDR has revolutionized it by seamlessly allowing communication across multi-generation devices for beyond-line-of-sight operation. This paper discusses integrating SDR into SATCOM systems and other applications like CubeSats, small satellites, and UAVs; it focuses on challenges of spoofing, GPS jamming, and the urgent need for low-latency communication. This study addresses current limitations by developing innovative solutions, like prototypes for SDR-based SATCOM modems, ground stations SDR-MES, and UAV safety mechanisms using SDR's programmability and flexibility.

Software-defined radio (SDR) devices have greatly improved communication networks by lowering RF design costs and time.[7] SDRs allowed programmers to enhance these readily controlled systems. Next, reconfigurability and adaptability are improved, which this article focuses on. SDR-based systems are improved by building an adjustable packet communication transmitter and receiver that uses CubeSat and small satellite communication windows. The transmitter changes signal qualities based on receiver feedback. The system can switch between many modes, but for simplicity and to demonstrate the concept, it is limited to three **Gaussian minimum shift keying (GMSK)** modulation rates: 2400 bps, 4800 bps, and 9600 bps, which are the most common in amateur, small satellites. The system program was written in Python and GNU Radio Companion (GRC).

Network-centric capabilities and data connectivity across multi-generation devices make beyond-line-of-sight communication tactically crucial. **Satellite communication (SATCOM)** is the only technology that can do this.[14] The SATCOM modem converts baseband data to RF band and vice versa. Common packet and communication standards make commercial off-the-shelf (COTS) SATCOM modems non-confidential and restrict user control for customized use. Due to 4G/5G networks, satellite constellations, and tactical communication, multi-generation machines must communicate reliably and at low latency.[10] Considering COTS modem restrictions, this paper offers a prototype software-defined radio-based SATCOM modem for geostationary satellites with a bent-pipe satellite transponder.

This paper discusses the **Software-Defined-Radio-based SDR-Micro-Earth-Station (SDR-MES)** satellite ground station architecture for Geostationary and Geosynchronous spacecraft TTC operations. Space missions depend on the ground station for Launch and Early Orbit (LEOP) and On-orbit activities.[9] SDR revolutionized satellite ground station design and operation by integrating high-performance wide-band radio front-ends with flexible FPGA-based digital backends that can be reprogrammed without hardware changes. This study describes the pragmatic method for miniaturizing the satellite ground station.

Spoofing and GPS signal jamming remain major hazards in general aviation and UAV operations. An inadequate **Global Navigation Satellite System (GNSS)** signal makes Unmanned Aerial Vehicles almost unmanageable, endangering airspace operations and ground residents.[15] This article examines how HackRF One 1.0, a low-cost Software-Defined Radio, affects UAV safety. Understanding how Software-Defined Radio devices affect Unmanned Aerial Vehicle safety is important, given their widespread usage and low cost. Artificial interference that might threaten increasing UAV airspace is unacceptable.

PROPOSED METHOD

The proposed method utilizes a Software-Defined Radio Adaptable Antenna System (SDR-AAS) to enhance satellite communication. The system integrates SDR with adaptable antennas, enabling real-time adjustments based on environmental conditions. This approach improves bandwidth utilization and signal quality, offering a flexible, dynamic solution for satellite communication.

In this case, the adaptable satellite antenna system will use SDR technology and IoRT, shown in Figure 1. This system for flexible and dynamic satellite communication will use this SDR technology to set up signal processing so that signals can be modulated and demodulated in a very efficient manner. The beamforming of this adaptable antenna system will dynamically vary with the needs of communication, and the changes will be made dynamically in frequencies to enhance satellite connectivity. It also enables remote control and monitoring of satellite components, with possible real-time adjustments and tracking of the system's performance. Satellites' telemetry and health data can be collected through this system, thus improving maintenance and optimization processes. Ground stations use IoRT to manage satellite communication links and configure and troubleshoot systems remotely when needed. With SDR and IoRT together, this configuration allows scalability, adaptability, and performance enhancement, making it the most suitable for satellite systems requiring flexibility to respond to ever-changing communications, environmental, or mission requirements. The result is reliable, efficient operations that can perform remote management.

$$e_g\ [L\text{-}OF\text{^''}\ ]:\rightarrow lW[lo\text{-}5vf]+9\ VF[2d\text{-}ks\text{^''}\ ] \tag{1}$$

Equation 1 assesses the relationship between adaptive antenna reconfigure parameters and dynamic operational variables, such as signal loss and variable frequency [*lo*-5*vf*]. In response to evolving

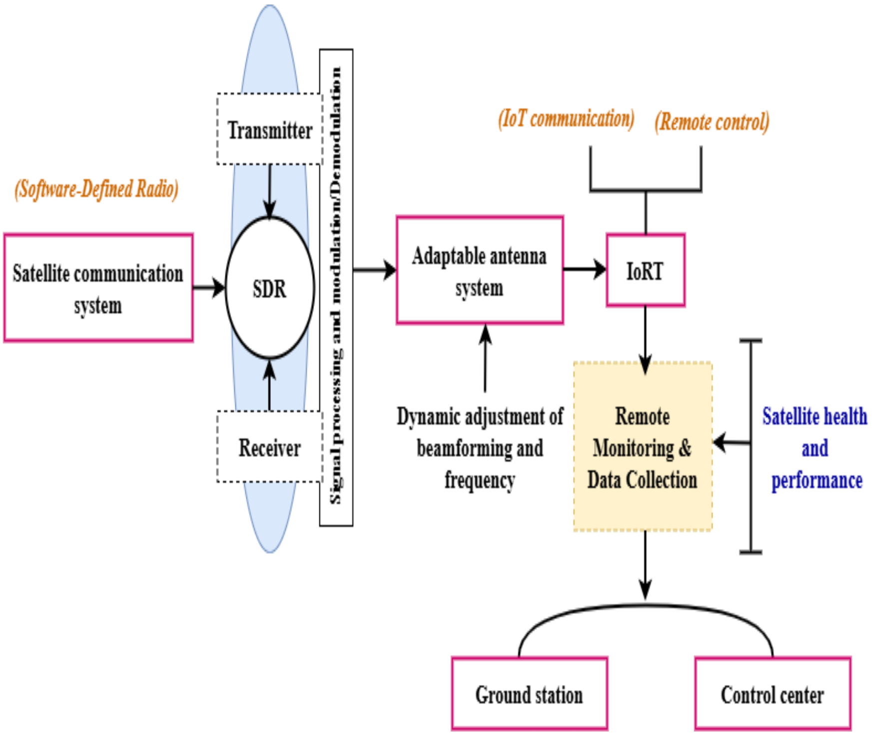

Fig. 1: Proposed method of SDR-AAS

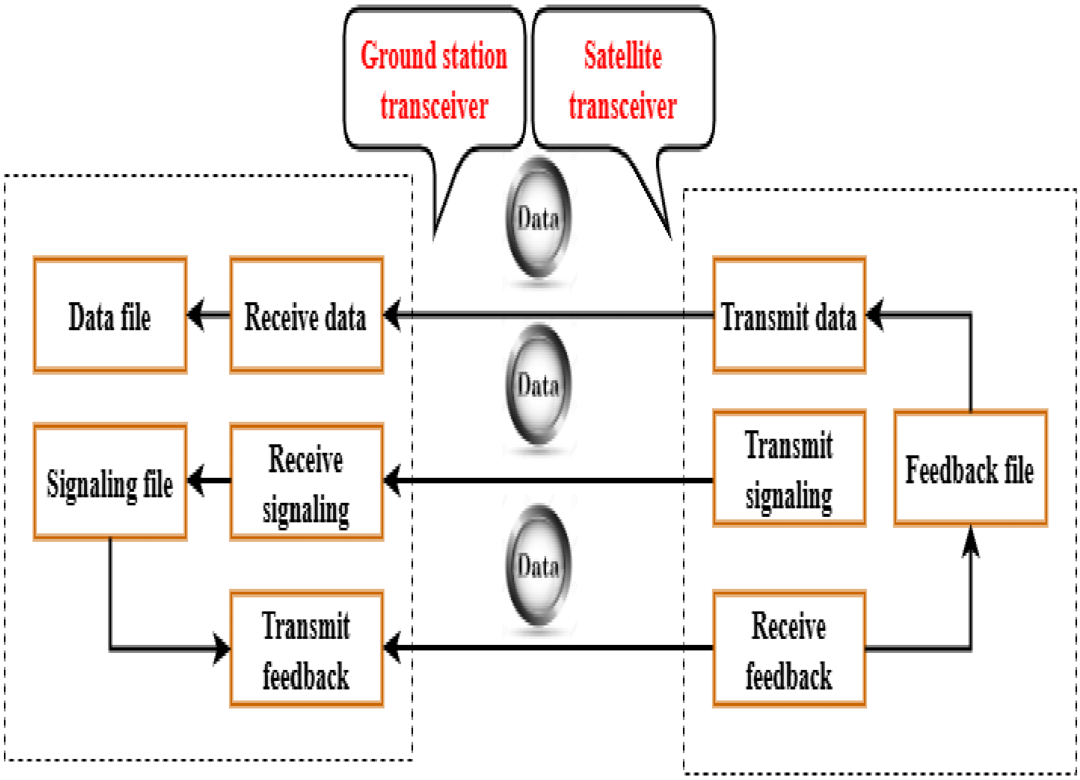

Figure 2: Data transfer within the SDR

communication needs, it measures the correlation between wavelength effectiveness (([2*d*-*ks*^”]) and immediate adjustments (e_g *[L-OF^”*]). This proves the SDR-AAS can improve spectrum use and maintain strong signal quality even under changing satellite settings.

$$r_F\ [4n\text{-}Psf^{\wedge}{}'']{:}\rightarrow j[2pf\text{-}bj^{\wedge}{}'']+8vw[l\text{-}of^{\wedge}{}''] \qquad (2)$$

The dynamic voltage and the transmission of signal constraints ($[4n\text{-}Psf^{\wedge}{}'']$) are modeled by the equation 2. The sentence explains $j[2pf\text{-}bj^{\wedge}{}'']$ how the interaction between frequency reconfiguration $8vw[l\text{-}of^{\wedge}{}'']$ and fluctuating external circumstances might improve performance. This proves that the SDR-AAS can automatically change the antenna settings to guarantee dependable data transfer in different kinds of satellite connections.

Figure 2 explains the data transfer process in a Software-Defined Radio system, describing the interaction between the ground station and the satellite transceivers. It presents the communication flow for data, signaling, and feedback. Each file plays a vital role in the successful and error-free transfer of information between the two systems. Data files represent the main data exchanged between the ground station and the satellite. The transceiver of the satellite receives the data sent out by the ground station. Conversely, the data from the satellite is transmitted by its transceiver and then received by the ground station's transceiver. Two-way transfer means there is always communication between the satellite and the ground station; hence, synchronization ensures continuous communication.

$$f_eR\ [l\text{-}Sl^{\wedge}{}'']{:}\rightarrow nJ[4nd\text{-}fp^{\wedge}{}'']+9vw[l\text{-}vaz^{\wedge}{}''] \qquad (3)$$

Equation 3 represents the connection between system flexibility $nJ[4nd\text{-}fp^{\wedge}{}'']$ and link stability in high-mobility situations. It emphasizes the interaction between environmental fluctuations f_{eR} and the dynamic number of nodes ($[l\text{-}Sl^{\wedge}{}'']$) to sustain strong communication. Here, the SDR-AAS is in action, demonstrating its capacity to improve connection stability and effectiveness in complex satellite communication settings.

The signalling file comprises the necessary control and management information for communication. This signaling file is sent from the ground station transceiver to the satellite transceiver, which processes and receives the information. Similarly, if the satellite requires transmitting control information back to the ground station, it sends the signaling file to the ground station transceiver, which receives it. This exchange ensures that both ends maintain proper coordination and control during communication. The feedback file represents the acknowledgement or response from one end of the system to the other. The ground station transceiver sends feedback data to the satellite, which receives it. The satellite transceiver sends feedback to the ground station transceiver; thus, each system remains aware of the status and progress of the data transfer. This feedback mechanism is integral for error detection and confirming successful transmission within the system.

Finally, the diagram explains the data, signal, and feedback files flowing back and forth from the ground station to satellite transceivers. The complexity makes it important to use the SDR system because it will support the effectiveness and reliability of satellite systems.

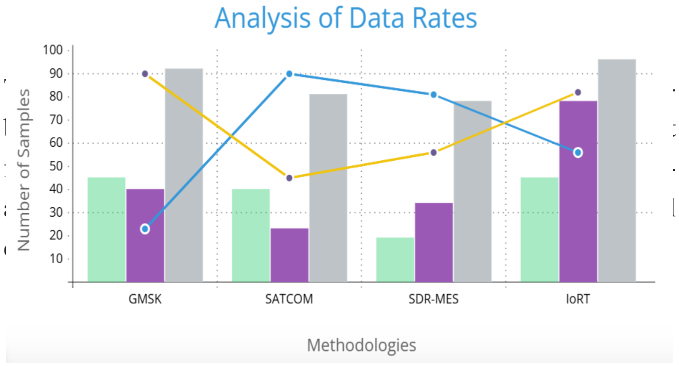

Fig. 3: Analysis of Data Rates

Figure 3 explains the data rate analysis of the proposed SDR-based adaptable antenna system and clearly shows improvements in bandwidth utilization compared to traditional satellite systems. With IoRT, this system dynamically adjusts the antennas' configurations based on the real-time environmental factors that lead to more efficient communication. Data rate fluctuations are minimized due to the adaptable antenna optimizing signal reception and transmission during varying conditions. This dynamic adaptation ensures the satellite communication system maintains high throughput in challenging environments. As results will demonstrate, enhanced reliability in delivering high-speed data supports mission-critical applications and improves overall system performance.

$$g_{sr}\ [l\text{-}nj^{\wedge}{}'']{:}\rightarrow Nj[3r\text{-}vd^{\wedge}{}'']+K[y\text{-}bw^{\wedge}{}'']\text{-}kv^{\wedge}{}'' \qquad (4)$$

By addressing interference caused by noise (g_{sr}) and bandwidth restrictions ($[l\text{-}n_j^{\wedge}{}'']$),), the system can maximize signal gain ($Nj[3r\text{-}vd^{\wedge}{}'']$)according to the given equation. To keep communication running smoothly, it controls both the distribution of resources (($K[y\text{-}bw^{\wedge}{}'']$) and the amount of variability ($kv^{\wedge}{}''$).. This improves signal quality and resource usage in the face of dynamic demands for satellite communication on data rate analysis.

- **Analysis of signal quality**

Figure 4 explains that signal quality in satellite communication is essential for maintaining reliable and noise-free data transmission. In the suggested system,

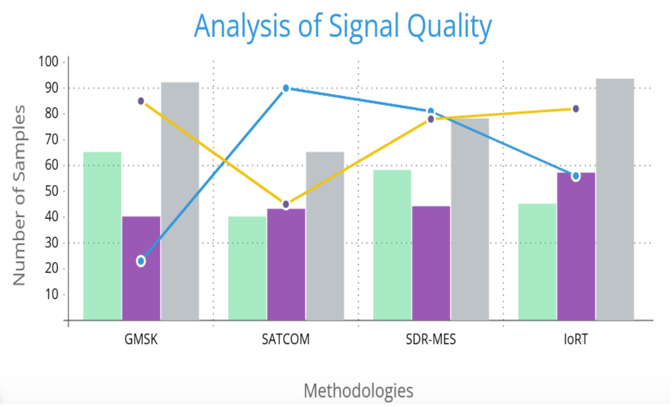

Figure 4: Analysis of signal quality

IoRT facilitates real-time monitoring and readjustment of antenna systems, which enhances signal strength with reduced interference. The adaptive antenna based on SDR dynamically adjusts its performance depending on changing situations like the positions of satellites and atmospheric variables, thus keeping the optimal signal quality. This makes the signal degrade less, and connections drop or become noisy less often. The analysis shows that the proposed system consistently delivers superior signal quality, even in complex environments, thus ensuring clear and interruption-free communication across satellite networks.

$$\forall_{KO}\ [J\text{-}Vf^{\wedge}{''}\ ]{:}\rightarrow Nw[koi^{\wedge}{'}\text{-}3rfk]+7\ vawe[lo\text{-}dfj^{\wedge}{''}\ ] \quad (5)$$

By modifying the variable frequencies ($\forall_{KO}$)) concerning the dynamic operational variables ($[J\text{-}Vf^{\wedge}{''}]$) and , the equation describes the universal adaptability (Nw[koi’]) of the SDR-AAS. The system’s ability to effectively ($[lo\text{-}dfj'']$) Communicate by optimizing the allocation of resources (-3*rfk*) and responding to environmental changes (7 *vawe*) is modeled. This highlights the importance of SDR-AAS in ensuring efficient and reliable communication across signal quality analysis.

The analysis shows that the proposed system provides higher data rates by optimizing bandwidth utilization through real-time antenna adjustment. Moreover, signal quality is improved due to the dynamic antenna configurations, reducing interference and reliable, clear communication across varying environmental conditions.

CONCLUSION

The SDR-AAS with IoRT eliminates almost all of the limitations inherent with the satellite communication system. Changing dynamic environmental conditions in real-time provide better data rates and an optimization of bandwidth usage. Improving the signal quality is also possible because it uses flexibility in the adaptability with the SDR technology. This new approach opens up opportunities for much stronger satellite communications systems to address the demands put forth by modern applications. An extremely important part in making this all work is to help out the SDR-AAS flexibleness by offering live data for modification of antenna settings, ground and space based sensors make up an Internet of Things, or IoRT. This integration makes it possible for the system to act independently, thus reducing the amount of manual intervention required and maximising the process’s efficiency. For example, an IoRT device is enabled to coordinate the alignment, resource sharing, and multi-satellite setups following satellites. This assists in making sure that it works at its best possible efficiency. In addition, the SDR-AAS system empowered with IoRT is highly scalable, hence ideal for use in the high scalability of satellite constellations. Scalability becomes a fundamental necessity in addressing the complexity of current satellite networks especially considering the emerging trend of LEOs as internet access satellites across the globe. Scaling to large satellite networks, where multi-satellite coordination becomes efficient for communication will form part of the future works of SDR-AAS. Second, higher sophisticated forms of machine learning algorithm in the predictive environmental analysis shall be integrated and an advanced optimization of the antenna towards optimum use. Testing shall occur under diversified real operational settings and harsh weather with substantial latency to prove robustness and scalability of the systems..

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