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Assessment of Satellite Coverage of Walker Constellation Types Across the Middle East

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ABSTRACT

This study addresses the critical challenge of selecting an optimal Walker satellite constellation architecture to ensure continuous and effective regional coverage. In particular, it focuses on a comparative analysis of two widely used configurations, Walker Star and Walker Delta, to determine which offers superior performance over a specific geographical region, namely the Middle East. Given the increasing demand for reliable satellite-based services in regional applications, identifying the most suitable constellation design is essential for both technical and cost-efficiency considerations. To tackle this challenge, a simulation-driven methodology was adopted using MATLAB and the Systems Tool Kit (STK). The study assumes a fixed number of satellites to maintain a controlled comparison framework. MATLAB was utilized for scenario initialization, parametric calculations, and visualization of results, while STK was employed for precise orbit modeling, ground coverage analysis, and dynamic performance evaluation. Key performance indicators such as gap duration, access duration, and percentage of area covered were computed and analyzed to quantitatively assess each configuration's effectiveness. The findings provide clear insights into the relative strengths and weaknesses of each constellation type and aim to support more informed decision-making in the design and implementation of regional satellite networks.

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1. INTRODUCTION

In this paper, a comparative analysis is presented between Walker Delta and Walker Star satellite constellation configurations, focusing specifically on their coverage capabilities for Internet of Things applications in Low Earth Orbit (LEO) environments. These two well-established constellation patterns offer distinct geometric arrangements and orbital phasing characteristics, which lead to significant differences in regional and global coverage performance. The paper aims to investigate how these differences influence key performance indicators such as coverage area, revisit time, and redundancy, especially when optimized for IoT connectivity. The study builds upon the work of Zhou et al. [1], who conducted a comprehensive coverage and capacity analysis of LEO satellite networks tailored to support IoT services. Their research highlights the necessity for optimized constellation layouts to meet the connectivity demands of large-scale IoT deployments. Similarly, Al-Hourani and Member [2] provide an analytical framework for determining the optimal altitude of dense LEO constellations in order to maximize downlink coverage probability, an important factor in constellation design. Further expanding on multi-objective optimization in satellite constellation architecture, Dai et al. [3] introduce a design framework that uses a genetic algorithm to simultaneously optimize multiple performance indicators. Their regional constellation model, inspired by the "Belt and Road Initiative," classifies over 70 countries into three target zones, enhancing the practical applicability of the system. Additionally, Qu et al. [4] emphasize the irreplaceable role of LEO constellations in providing IoT services, citing their low latency, global reach, and cost-effective deployment as major advantages over traditional terrestrial networks. Their work underlines the need for constellation design that specifically addresses the unique communication requirements of IoT nodes. Finally, Tani et al. [5] propose an innovative approach using evolutionary algorithms for regional satellite constellation design without relying on inter-satellite links. Their model ensures continuous coverage of selected areas while accounting for mutual visibility, which is particularly critical in scenarios where real-time regional service is essential. In the work by Capez et al. [6], sparse constellations for direct-to-satellite Internet of Things (DtS-IoT) were proposed, where devices connect directly to LEO satellites acting as orbiting gateways, eliminating the need for ground infrastructure. Their approach aimed to minimize the number of in-orbit DT-S-IoT satellites by optimizing the delivery delay inherent to resource-constrained IoT services and by careful positioning of the satellites. They also examined realistic constraints from LoRa/LoRaWAN and NB-IoT standards, particularly focusing on the allowable maximum time gap between successive satellite passes. Luo et al. [7] proposed an ICN-based framework for LEO mega-constellations to enhance IoT services via in-network caching. They introduced a Random Forest-based caching algorithm (CARF) that improves cache efficiency by predicting content popularity and satellite location. Melaku and Kim [8] proposed a CubeSat constellation design for multi-mission Earth observation using NSGA-II, achieving a trade-off between the number of satellites, average revisit time, and coverage performance. Tian et al. [9] proposed a self-organising small satellite constellation architecture with inter-satellite links (ISLs) to enable autonomous control, ISL establishment, and channel selection for IoT and MTC connectivity in LEO. Yan et al. [10] developed a unified framework for LEO satellite broadband constellation design by combining network performance, coverage, and stability, and solved it using NSGA-II. Akah & Elfiky [11] designed and evaluated a small IoT satellite constellation to provide continuous coverage over Egypt, focusing on smart agriculture and water management. They also identified optimal ground station locations and analyzed latency and handover performance. Torkamani et al. [12] explored an indirect deployment method that utilizes Earth's oblateness perturbation along with the satellite's propulsion subsystem to distribute satellites across multiple orbital planes. Eftekhari et al. [13] also conducted a scientometric analysis to examine the structure and scientific mapping of "satellite constellations" worldwide, focusing on two leading countries: the United States and China. In addition, they compared the research outputs of the United States, China, and the rest of the world. Zohrabzadeh Bozorgi & Naghash [14] designed and proposed several hybrid satellite constellations combining LEO and GEO satellites to provide navigation and positioning services for users in Iran.

A review of relevant literature highlights several previous studies that have examined satellite constellations for communication and IoT, but there remains a gap in a direct, simulation-based comparison between Walker Delta and Walker Star configurations under controlled conditions. To address this, we developed a simulation framework model, simulated, and evaluated the two constellation types using the same number of satellites over a fixed geographical region. We computed performance metrics, including access duration, gap duration, and percentage of area covered. Through this synthesis of prior research and our own simulation-based analysis, the paper aims to offer new insights into how constellation geometry, particularly the choice between Walker Delta and Walker Star patterns, can be tailored to optimize service quality, capacity, and resilience in regional deployment scenarios.

2. SIMULATON

Before proceeding to the simulation discussion, a brief explanation of the Walker constellation is presented. Among various satellite constellation configurations, the Walker constellation stands out as the most symmetrical and well-known structure. This constellation consists of a set of circular orbits with identical altitude and inclination, uniformly distributed around the Earth. In this configuration, the right ascension of the ascending node (RAAN) of each orbital plane is evenly spaced within the reference plane, such as the equatorial plane, and satellites are equally spaced within each plane. This orderly and symmetric arrangement enables the creation of global or regional coverage with a fixed and predictable pattern, making it an ideal choice for numerous communication and navigation applications. However, it is important to note that in Low Earth Orbit (LEO), employing only a single Walker constellation with a full RAAN spread of 360° may pose challenges in achieving true global coverage [15]. The geometry of a specific Walker constellation can be described using three parameters: T/P/F, where T denotes the total number of satellites in the constellation, P is the number of orbital planes, and F represents the phase shift between satellites in adjacent planes. Assuming S is the number of satellites per orbital plane, the following relation holds:

$$T = P.S \tag{1}$$

To calculate the angular offset between satellites in adjacent planes, the phasing parameter F is multiplied by $\frac{360°}{\mathrm{T}}$. In this configuration, the first satellite in the first orbital plane is considered the reference satellite. The orbital parameters of the j-th satellite in the i-th plane of the Walker constellation are defined as follows [16]:

$$\begin{cases} a_{ij} = a_0 \\ e_{ij} = e_0 \\ I_{ij} = I_0 \\ \Omega_{ij} = \Omega_0 + \frac{360°}{P}.(i-1) \\ \omega_{ij} = \omega_0 \\ M_{ij} = M_0 + \frac{360°}{P.S}F.(i-1) + \frac{360°}{S}.(j-1) \end{cases} \tag{2}$$

In this study, the focus area is the Middle East region with the borders of the countries in Fig. 1. Initially, a Walker Delta constellation with 10 orbital planes and 3 satellites in each plane was simulated. The simulation schematic in STK is shown in Fig. 2. The orbital parameters of each plate are as in Tables 1 and 2. Also, the sensor cone half angle for each satellite is 45°.

Table 1. The orbital parameters for Walker Delta.

Parameter	*Value*
$i(deg)$	*45°*
e	*0*
$h(km)$	*1000*
F	*0*

Table 2. The orbital parameters for Walker Star.

Parameter	*Value*
$i(deg)$	*90°*
e	*0*
$h(km)$	*1000*
F	*0*

Also, for the Walker Star constellation, these steps have been completed with exactly the same orbital specifications. The simulation schematic in STK is shown in Fig. 3. Finally, the requested graphs were extracted and examined in MATLAB, which are explained in the following sections.

Fig. 1. Countries in the region studied in the simulation.

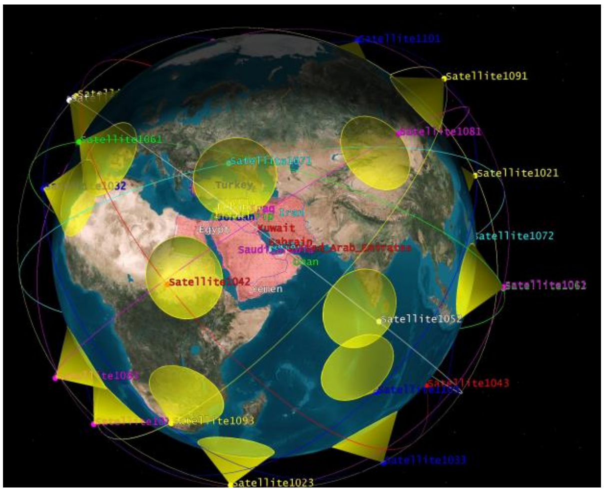

Fig. 2. Walker Delta constellation simulation.

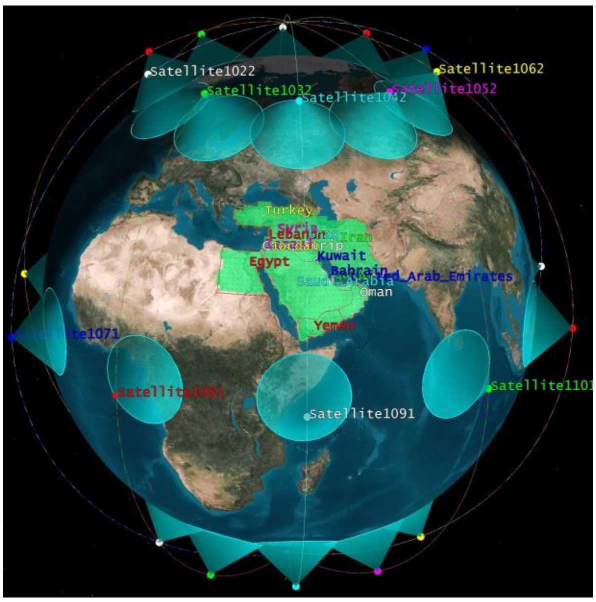

Fig. 3. Walker Star constellation simulation.

3. RESULTS

Figure 4 and Fig. 5 show the coverage time graph of the walker delta and the walker star constellation. What can be initially concluded from these two graphs is that both quickly reach 100% cumulative coverage, indicating that both systems eventually cover the entire area of interest. In the Walker Delta system, fluctuations range from about 5% to 70%, the frequency of fluctuations is higher, and most of the time, the instantaneous coverage is higher. In the Walker Star system, the fluctuations are between about 5 and 65 percent, the frequency of the fluctuations is lower, the coverage peaks are fewer, and the gaps without coverage are longer.

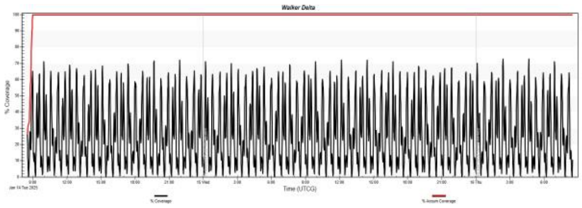

Fig. 4. Coverage time of the Walker Delta constellation.

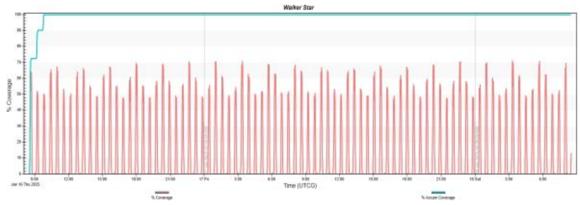

Fig. 5. Coverage time of the Walker Star constellation.

Overall, the Walker Delta system has more stable coverage and fewer non-coverage times. The coverage pattern repetition period is shorter in the Walker Delta, while the Walker Star has larger coverage gaps, which can be problematic for some applications. The Walker Delta is better suited for applications that require more continuous coverage, while the Walker Star, with its larger coverage gaps, may be better suited for applications that do not require continuous coverage, according to its chart. Figure 6 and Fig. 7 show the coverage by latitude graph of the walker delta and the walker star constellation. For the Middle East region, Walker Delta has about 20% to 46% coverage, and Walker Star has about 9% to 19% coverage relative to latitude. Both systems show a similar coverage pattern at low latitudes and have a significant increase in coverage at higher latitudes. Walker Delta consistently has better coverage; for example, at a latitude of 30 degrees, Walker Delta has at least 20 % coverage, while Walker Star has at least 9 % coverage at the same latitude. Given that most Middle Eastern countries are located between latitudes 15 and 35 degrees, the Walker Delta seems more suitable for covering the Middle East.

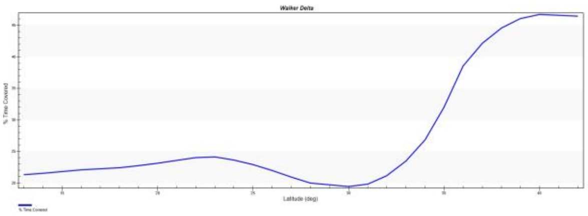

Fig. 6. Coverage by latitude graph of the Walker Delta constellation.

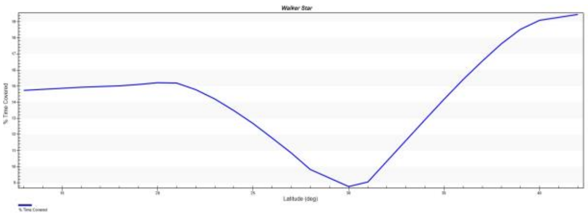

Fig. 7. Coverage by latitude graph of the Walker Star constellation.

Gap duration refers to the time interval between two consecutive access periods when a satellite (or constellation) is not in view of a specific ground location and therefore cannot communicate with or observe it. This parameter is especially important in applications that require frequent or continuous data exchange, such as IoT networks, surveillance, or disaster monitoring. Shorter gap durations imply more frequent access and better temporal coverage. Gap duration is influenced by factors such as the number of satellites in the constellation, their orbital configuration, and the ground station's location and visibility conditions. In constellation optimization, minimizing gap duration is often a key objective to ensure timely and reliable data collection. Figure 8 and Fig. 9 show the gap duration graph of the walker delta and the walker star constellation. In terms of gap duration, Walker Delta has shorter gaps (up to 40 minutes) while Walker Star has longer gaps (up to 100 minutes). Walker Delta has a more uniform distribution of gaps, while Walker Star shows more abrupt and step-like changes in the gap distribution. Overall, Walker Delta is more suitable for telecommunications services that require more continuous coverage due to shorter gaps, a more uniform, and predictable distribution.

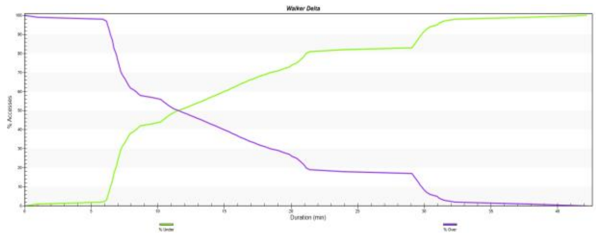

Fig. 8. Gap duration of Walker Delta constellation.

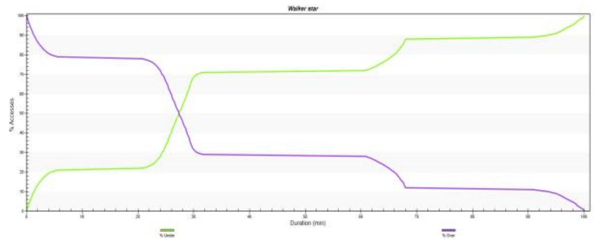

Fig. 9. Gap duration of the Walker Star constellation.

Access Duration refers to the continuous time interval during which a satellite maintains a communication or observation link with a specific ground point or region. This parameter is crucial in evaluating the effectiveness of a satellite system, especially for applications like remote sensing, IoT data collection, and real-time communications. Longer access durations typically allow for more data to be transmitted or for higher-quality observations to be made during each pass. Access duration depends on various factors, including satellite altitude, orbital inclination, ground station location, antenna beamwidth, and minimum elevation angle constraints. In constellation design, maximizing access duration helps improve coverage quality, reduce data latency, and increase system reliability. Figyre 10 and Fig. 11 show the accesses duration graph of the Walker Delta and the Walker Star constellation. In terms of access duration, both systems have a similar pattern in access times. The access times are roughly the same for both systems. The Walker Delta is a little more consistent, but only slightly.

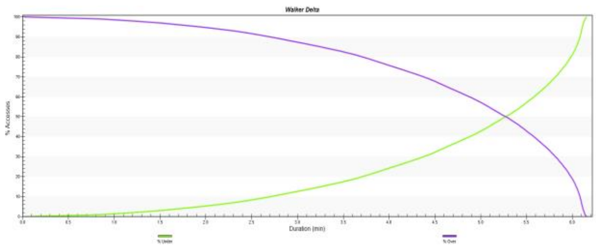

Fig. 10. Access duration of the Walker Delta constellation.

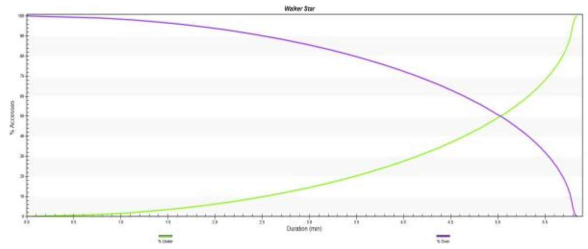

Fig. 11. Access duration of the Walker Star constellation.

The Figure of Merit (FoM) is a comprehensive metric used to evaluate the overall performance of a satellite constellation by combining multiple technical and operational parameters into a single, normalized value. It provides a balanced framework for assessing trade-offs between different design options and supports optimal decision-making tailored to mission-specific goals. In the context of satellite systems, the FoM typically encompasses factors such as coverage area, revisit time, latency, number of satellites, power consumption, data throughput, link availability, and cost efficiency. Additional parameters like system reliability, lifetime, and accessibility of ground stations may also be incorporated, depending on the application. By weighting these elements according to their importance, the FoM enables a holistic comparison of alternative configurations and plays a key role in the design and optimization of modern satellite networks, particularly in domains such as IoT, Earth observation, and smart agriculture. Figure 12 illustrates the FoM (Figure of Merit) variation over a single day for a satellite constellation configured in the Walker Delta pattern. The minimum, maximum, and average FoM values are represented by red, blue, and green lines, respectively. As depicted, the average FoM exhibits significant fluctuations throughout the day, with several sharp drops in the minimum value indicating potential gaps or non-uniformity in coverage. In contrast, Fig. 13 shows the FoM performance for a Walker Star configuration under the same temporal conditions. This setup demonstrates notably higher and more stable FoM values, especially in terms of minimum and average performance. The smoother trends and reduced variability in the Walker Star configuration highlight its superior consistency and effectiveness in maintaining continuous coverage compared to the Walker Delta counterpart.

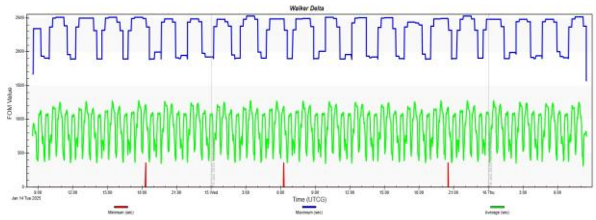

Fig. 12. Temporal variation of FoM values for the Walker Delta constellation.

Fig. 13. Temporal variation of FoM values for the Walker Star constellation.

Figure 14 presents the variation of the FoM as a function of latitude for the Walker Delta constellation configuration. The minimum, average, and maximum values are denoted by red, green, and blue curves, respectively. As shown, the FoM values remain relatively high and stable at lower latitudes but begin to decline sharply beyond approximately 33° latitude, reaching their lowest values near 37–41°, indicating a significant drop in coverage or revisit frequency in higher latitude regions. In contrast, Fig. 15 displays the same analysis for the Walker Star configuration. This constellation demonstrates not only higher FoM values across all latitudes but also superior stability, maintaining excellent performance until around 36°, beyond which a similar but less severe drop is observed. These results suggest that the Walker Star configuration provides more uniform and robust performance across a wider range of latitudes compared to the Walker Delta architecture.

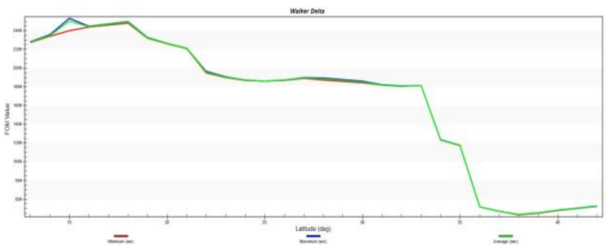

Fig. 14. Variation of FoM values across different latitudes for the Walker Delta constellation.

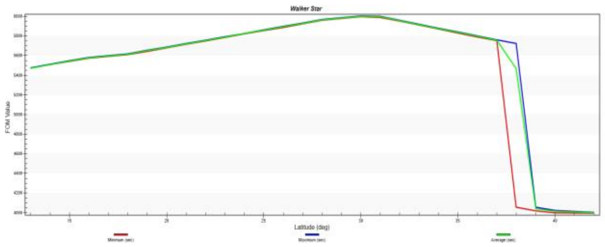

Fig. 15. Variation of FoM values across different latitudes for the Walker Star constellation.

4. CONCLUSION

In this study, the performance of Walker Delta and Walker Star constellation configurations was evaluated over the Middle East region using identical orbital parameters and an equal number of satellites. Simulation results based on key metrics such as cumulative coverage, coverage by latitude, and revisit time (gap duration) demonstrated that the Walker Delta configuration outperforms Walker Star in terms of more continuous coverage, shorter revisit intervals (up to 40 minutes), and higher coverage ratios within the target latitude range (15°–35°). These characteristics make it more appropriate for regional applications that demand persistent connectivity, such as telecommunications services. However, supplementary analysis based on the Figure of Merit (FoM) accounting for quality, stability, and uniformity of access showed that Walker Star offers higher average FoM values and more stable performance over time and across latitudes, suggesting its potential advantage in scenarios where service quality consistency is more critical than revisit frequency, such as in IoT or Earth observation missions. Ultimately, the choice between these two architectures should be driven by the specific mission requirements, whether the priority is a higher revisit rate or uniform access quality. It should also be emphasized that these conclusions are derived from a region-specific analysis focused on the Middle East, and the results may vary significantly for other geographic areas or global-scale constellation designs.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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