Enabling 5G on the Ocean: A Hybrid Satellite-UAV-Terrestrial Network Solution

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***Abstract*—In this research paper we will look at the problem of Maritime communication networks behind far behind the existing 5th Generation technology that exists mainly in the terrestrial domain all across the world. We will also look at the Why's of this problem which deals with mostly the unpredictability of deploying technology at sea and across oceans. To overcome the problem we will discuss the use of Unmanned Aerial Vehicles (UAVs) integrated along with the existing technology which consists of Satellites and Terrestrial Base stations (TBSs). We will also see the practicality of the proposed solution as well as the prerequisites considered and the specifications needed.**

***Index Terms*—Unmanned Aerial Vehicle, Terrestrial Base Station, Inmarsat, Maritime Communication Networks, TD-LTE, High Altitude Platforms, Ka-band, High Gain Antennas, Automatic Identification System, Channel State Information, DJI Inspire 2, ZEROTECH ZT-30V, CEEWA X-9, JOUAV CW100, AEE AU300, Ziyan UAV Blowfish A2, Rising Fly MixOne**

I. Introduction

Due to expansion of international trade and increased defense activities of countries, marine activities have seen an upsurge and a continuous development due to which the need for maritime broadband communications has increased exponentially. To meet this demand for higher data rates on the ocean which are currently only a few Mb/s [1] making them drastically lesser than the terrestrial 5G network rates in Gb/s, maritime communication networks (MCNs) are demanding immediate attention.

There have been multiple approaches to develop MCNs to overcome this problem, adopted by different companies and organizations some of which are:

1) Time Division Long Term Evolution (TD-LTE) Trial Network by Ericsson and China Mobile-
This trial network was established in China in the Qingdao Sea Area, where to expand the 5G network to the ocean Terrestrial Base Stations (TBSs) were built along the coastal areas. This helped in extending the broadband services to about 10 kilometers away from the coast but not any further than that [2].

2) Projects BlueCom+ [4] and TRITON [3] -
These aimed at further extending the network coverage using multiple hop systems. These were having oceanic vessels which functioned as relay nodes as well as tethered balloons at high altitudes to augment the coverage. This helped in providing broadband services up to 150 kilometers off the coast with data rates upto 3 Mb/s. Nonetheless, this method was not reliable because of the lack of flexibility in the multiple hop system. Deploying vessels on the ocean will limit the area covered due to fixed lanes that have to be followed for safety purposes which would result in coverage holes in areas where the vessels couldn't reach.

3) Inmarsat-5 Marine Satellite-
This offers coverage over remote areas far off from the coast and is better than the former Inmarsat Satellite which had drastically low data rates in comparison to 5G terrestrial networks owing to the longer transmission distances. This however to overcome the problem was stationed in the Geostationary Earth orbit (GEO) thus giving Ka-band network upto 50 Mb/s forward data rates and 10Mb/s on return [5].

4) Iridium NEXT Satellite System-
This satellite system deployed 66 satellites in the Low Earth Orbit (LEO) offering Ka-band network with upto 8 Mb/s data rates [6]. Nonetheless, the huge delay in communication remains the drawback. Also dedicated terminals are needed for these developments which are possible through high gain antennas (HGAs).

5) Loon Project using High Altitude Platforms (HAPs)-
This used super-pressure balloons stationed at a height of 20 kilometers for better coverage over remote areas [7]. The network data rates were still only upto 10 Mb/s.

As we have seen, none of them incorporated Unmanned Aerial Vehicles (UAVs) in the Maritime Communications networks. In the terrestrial realm though, various studies have been conducted on the UAV enabled communication which shows it to be one of the best solutions for enhancing dynamic network coverage [8], [9]. We will study in this paper how we can extend these capabilities of UAVs to provide on-demand network coverage in maritime routes by functioning as agile aerial platforms above the ocean. UAVs offer more agility as compared to the balloons due to the balloons having superior mobility at low altitudes and unlike TBSs and marine satellites, can better fill the coverage holes where vessels can't reach. Now with integrating UAVs with the existing MCNs we will get a Hybrid Satellite-UAV-Terrestrial Network architecture [18]. Concerning this Hybrid, we will also dive into scheduling of UAVs based on the demand on the vessels in sea routes by predicting the vessel's movement on the routes from pre collected data.

We will then see challenges and the possible solutions

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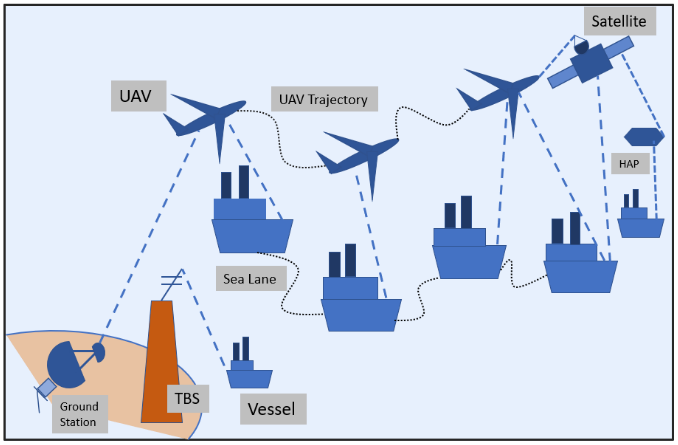

Fig. 1: Hybrid Satellite-UAV-TBS Network Illustration

of integrating UAVs into the MCNs as well as coordination issues arising from the interaction of UAVs with existing satellites and TBSs.

II. Mobility Comparison between UAV, Satellites and TBSs

Terrestrial Base Stations (TBSs)-
These only provide a limited mobility due to various restrictions. These can be only stationed on highly-elevated towers along the coast and on mountains. The maximum mobility it can support is by using shipborne base stations which is still limited by the area accessible because of the fixed sea routes vessels have to follow for safety purposes.

Satellites-
The deployment of satellites is largely restricted according to the theory of Orbital Dynamics. This can be ascertained by demonstrating how the satellites Iridium NEXT and Inmarsat-5 both have to follow pre decided orbits of revolution as decided by astrodynamics which cannot be changed arbitrarily. Thus to achieve global network coverage LEO constellation is necessary although expensive.

UAVs-
Out of all, the Unmanned Aerial Vehicles offer the maximum mobility because of its flexible deployment. This is because of the following factors:
They can provide broadband communication services to target vessels on-demand by flying with the said vessel.
They can improve the transmission rates significantly by flying close to the target users thus making the access point closer as well. This also shortens the latency in communication.

However, it has a few shortcomings such as:
a) Limited Endurance due to finite energy available onboard.
b) Difficulty in deploying UAVs on the ocean sometimes due to unpredictable weather conditions.

These shortcomings can however be resolved by:
1) Considering all the constraints while scheduling UAV deployment to better optimize it.

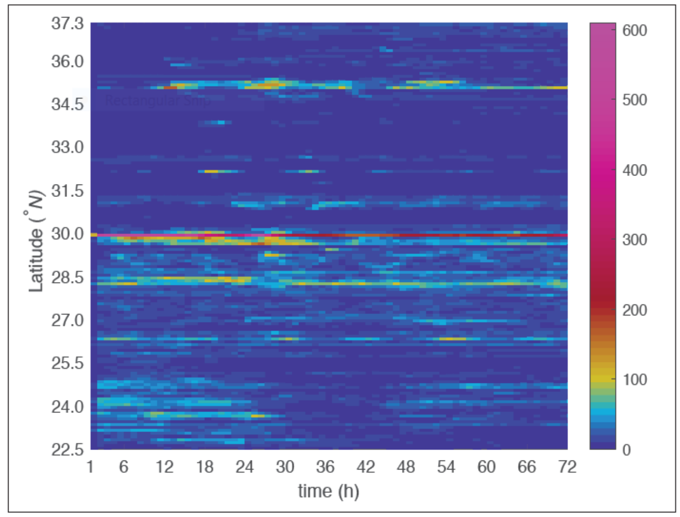

Fig. 2: Case Study

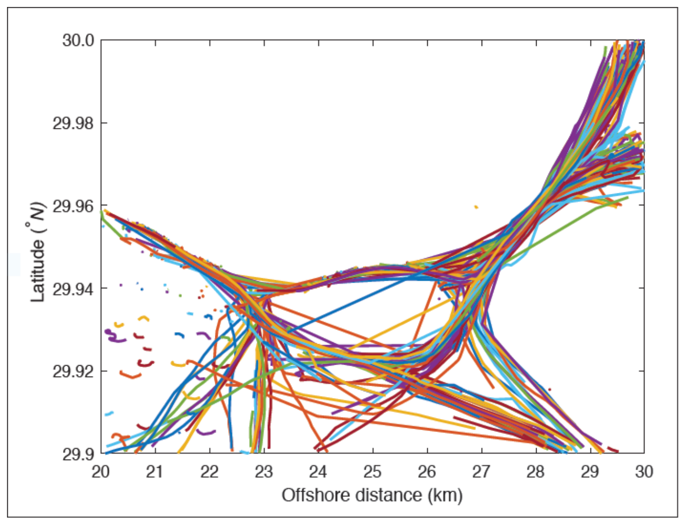

Fig. 3: Case Study

2) Improving Efficiency in UAV communications on the ocean by predictable mobility and by studying various characteristics of maritime user and vessel distribution.

III. Distinctive Maritime Users & Vessels Characteristics

Studying user and vessel characteristics is very important to effectively schedule UAVs. Maritime communication is very different from the terrestrial one because in contrast to the terrestrial environment where the users have random movement, maritime users which are the vessels are restricted to pre decided sea/ocean routes thus making it important to study their mobility patterns by tracking the said users.
This tracking can be achieved by using the Automatic Identification System (AIS) which is a transponder system and works by punching in a ship/vessel's state information, it's speed, position in the sea with respect to sea routes and where it's heading to name a few.

A case study done in a coastal region of China can be referenced here to highlight mobility patterns and thus helping us in effective scheduling of UAVs. As also shown in the Figure 2, we have fixed a range of latitudes and a 3 day period to study vessel distribution in the region with a 20-30 kilometres offshore distance. Then we next study the number of ships/vessels which show up in a square region with 0.1° latitude length and width 10 kilometres. This square is studied in periods of an hour where for each hour, one square is accumulated as one data point. Dark blue region in the graph which is the most prominent indicates 0 to very few users in an area and the red line indicates the existence of a sea lane. These sea lanes can be further demonstrated by the Figure 3 which is cumulated from AIS data collected for over 610 vessels in a period of 1 hour. Studying this we see that user distribution on the ocean is sparse both with respect to time and space. Maximum vessels follow the assigned sea lanes regularly and thus we can predict future mobility patterns thus usually easily tracking them even in the extensive ocean.

IV. On-Demand Network Coverage Model with UAVs

UAVs can be made to function in the following ways to provide broadband services: In the areas that are off limits for the existing MCNs, UAVs can be dispatched where they either guarantee long term network services by moving alongside the vessel or they follow a serve-and-leave pattern.

In both these methods, the UAVs function quite contrastingly to conventional terrestrial UAV networks wherein users are either both randomly distributed and moving or else follow fixed patterns. After completing the transmission task the UAV heads to a set up vessel/port with a charging station or to its next vessel in the service queue.

UAVs accomplish the task of on-demand network more efficiently than the other components of the hybrid which are satellites and TBSs because of UAV's mobile agility. Whereas in satellites and TBSs the dynamic transmission costs a lot because of expensive array antennas. UAVs also fare better as these accommodate the demands of sparsely timed communication requests with the help of their dynamic schedules based on time predictions.

V. Challenges of UAV Integration and Proposed Solutions

We can broadly classify the obstacles faced while introducing UAVs into existing MCNs as follows:

1) Harsh Maritime Conditions:
The unpredictable maritime environment further poses 3 intricacies:
a) Optimal Wind Speed-
Weather conditions have an upper hand on the deployment of UAVs as conditions such as high tidal waves, thunderstorms, cyclones and typhoons are common at sea. These can cause wind speeds to shoot up to as high as 30 metres/s which makes it extremely unfit to fly a UAV. UAVs are only meant for favourable weather conditions with the maximum withstandable wind speed being not more than 17.1 metres/s.

Type	Unmanned Gyroplane			Fixed-Wing UAV			Helicopter	
Company	DJI	CEEWA	Rising Fly	JOUAV	ZEROTECH	JOUAV	Ziyan UAV	AEE
Model	Inspire-2	X-9	MixOne	CW10	ZT-30V	CW100	Blowfish A2	AU300
Wind Resistance (m/s)	10	12	/	10.8-13.8	10.8-13.8	13.9-17.1	17	/
Cruising Speed (km/h)	/	/	/	72	90	100	70-90	130
Maximum Speed (km/h)	94	72	/	/	130	/	130	/
Max Flight Duration (h)	0.5	1	5	1.5	7	4-8	1	4
Driving Force	Electric	Electric	Oil-Electric	Electric	Oil-Electric	Oil	Electric	Oil

Fig. 4: Characteristics of Various UAV Models

Solution- To overcome this we need to choose the variant of UAV to be deployed extremely carefully after going through factors such as:
i) Type
ii) Company
iii) Model
iv) Wind Resistance
v) Cruising and Maximum Speed
vi) Maximum Flight Duration
vii) Mode of power generation

b) Endurance Times of UAVs-
In the terrestrial environments landing the UAV drones to recharge is not a difficulty, whereas in maritime environments this need becomes a huge restriction to their deployment.

Solution- To overcome this we can implement the following:
i) Deploying the UAVs when offline, while remaining in bounds of the restrictions.

ii) Using AIS data (as seen previously) to know the demand for broadband network requests.

iii) Deploying UAVs within their optimal duration of endurance thus effectively filling network coverage holes.

iv) Offline and Online Collaborative Model- Pre deploying the UAVs while offline will help in reducing the serving latency as well as fill coverage holes. This makes it better than temporarily dispatching the drones upon user requests on the ocean. Offline deployments should have their time durations in accordance to the predictions of maritime weather conditions and environment. Last but not the least, online mode of deployment should be activated in extremely changing weather conditions where it will provide greater adaptability.

c) Onboard Energy Limitations-
One must carefully determine the duration of deployment of a UAV considering the residual energy onboard. The onboard energy resources limit the maximum flight duration to 8 hours

and thus one has to deploy service stations for replenishment of energy on the ocean.

Solution- We can resolve this problem by doing the following:
i) We can assign specific vessels for replenishment as service stations. Though the area covered by these vessels will be limited to their fixed sea lanes. This can further be solved by dedicating service stations which are vessel-specific and according to the location of the user vessel on the ocean.

ii) According to the table in Figure 4, we can see that UAVs can be divided into subcategories of Unmanned gyroplane, Vertical take-off and landing fixed-wing and lastly the Helicopter variant. Out of these if we consider the possibility of solely coastal service stations, then with an average of 370 kilometres of offshore distance only the fixed-wing category UAV that is oil powered would be suitable. This will be ascertained by the maximum time of flight and cruising speed of the UAV.

iii) Having a cluster/swarm of UAVs becomes important for continuous communication as a single UAV is limited by energy. Thus we have to effectively schedule this swarm of UAVs. Another thing that can be noticed is that due to the sparse distribution of users on the ocean, each UAV would only be functioning part-time thus during its flying time it will be idle.

iv) During the duration of time when a UAV is flying to and from a service station which can be either vessel based or terrestrial, a UAV in the neighbouring swarm having enough residual energy can be sent off to guarantee the continuous network coverage.

v) Having multiple UAVs makes it important to optimize the number of scheduled UAVs which will be more time and cost effective.

vi) In the worst case scenario where none of the neighbouring UAVs have enough residual energy the vessels will be supplied with degraded services from the existing MCNs upon request.

2) Issues in Coordination:
Maritime UAVs are dependent on the pre existing MCNs for backhaul links unlike terrestrial UAVs where backhaul isn't totally necessary given the extensive terrestrial coverage of networks. These MCNs currently are not completely sufficient and reliable to have a wireless backhaul on the ocean. Only UAVs which are near the coastal regions can be supported with backhaul links by TBSs.

Solution- We can do the following to resolve coordination issues:
i) Satellites can be used for wireless backhaul when the UAVs are far off from coastal regions. This solution comes with its drawbacks of communication rates being limited and a very large delay which can also lead to latency issues. To implement this solution we also need to equip UAVs with airborne antennas which are high gain in nature.

ii) While scheduling the UAVs this backhaul issue should be taken into consideration. We should also take note of the information delay tolerance to allow short term and provisional outage of backhaul by using data caching on the UAV. This design will take into account the trajectory of UAV, caching and communications.

iii) MCN's have particular spectrums for communication over which they broadcast information and due to multiple MCN's there can be spectrum scarcity. The spectrum of the pre existing MCNs can be shared by the UAVs to solve this problem.

iv) The problem is further complicated as unlike terrestrial environments where communications infrastructure is fixed, here there is a lot of mobility which causes interference between different channels [10]. To solve this the interference distribution can be predicted by studying the trajectories of the UAV drones. Thus we will be able to synchronize TBSs, UAVs and satellites with coordination of interferences according to particular processes.

3) Inaccurate Channel State Information and Limitations:
Channel state information is useful in acquiring the trajectory or location of UAVs and for effective allocation of resources thus finally improving the service quality. Though the problem here is that the maritime environment and conditions makes it very difficult to acquire accurate CSI. This is because of the following factors:
a) The trajectories of maritime UAVs are pre planned while offline which makes the CSI retrieved to be predictive rather than instantaneous. This makes the task of optimizing the trajectory with the retrieved CSI incredibly hard.

b) The CSI between the satellite/TBSs users and UAVs needs to be retrieved to improve the efficiency of shared spectrums between the various components of a MCN. This however is difficult because direct connection links do not exist between satellite users and UAV for CSI feedback. If we do want to get this CSI then it has to be exchanged through a specific central processor between the subsystems of satellite and the UAV. This will lead to unwanted latency and delay.

Solutions- To solve these shortcomings we can do the following:
i) In the real life we could predict CSI information which is large scale,(which includes departure and arrival angles, shadowing and path loss) using previously retrieved/measured data as these are related to positions of the transceiver [11].

ii) Large Scale CSI can be very helpful in maritime conditions to better optimize a MCN. To do this, a radio map can be created on the ocean which focuses on shipping lanes and for any of the given positions produces a large scale CSI.

iii) To further improve the large scale CSI we can create a look up table for acquiring CSI rather than depending on the pilot based feedback and channel estimation. This will be created by first measuring large scale CSI of sole vessels and UAVs that are dispatched for this purpose. Secondly this can be further improved by continuously updating the map using channel knowledge gained from the communications data, in an online manner for improved resolution.

iv) In the real life the radio map technology should be developed for the reliable optimization of UAV trajectories and allocation of resources having large scale CSI.

VI. Numerical Example and Discussions

In the Figure 1 we can see all the components of the hybrid MCN. Here we can also note that the UAVs on the demand of the user vessels are dispatched and after the completion of the transmission flies back to its service station vessel. For the first three positions of the UAV its trajectory is pre decided depending upon the predicted large scale CSI and information of the shipping lane of the vessel on the ocean. For the backhaul, the UAV remains in communication with the TBS nearest to it. For the access side, the UAV and the satellites will share common spectrum according to ongoing particular processes during network transmission.'I' represents the interference temperature limitation which controls the interference between UAV and satellite users. The interference between the backhaul and access links is also managed by having different time slots and sub processors/ carriers. For the pre deployment of the UAV drone we will take only large scale CSI into consideration and the composite channel which is considered includes Rician fading and path loss [12], [13]. Rician fading is a defective signal propagation model wherein a signal gets partially cancelled by itself. This happens due to multiple changing paths of transmission of the signal.

There are multiple constraints such as 'P-max' which is the maximum transmission power, residual energy 'E' and 'l', the interference temperature limitation [14]. According to these constraints the transmit power and the trajectory of the UAV drone is optimized for the best results. The best result is when the performance of the user who is facing the worst-case scenario is promoted. This means we have to maximize the minimum achievable rate. We have to take the assumption of the shipping lanes of the vessels being already known to us and the speed of the vessel is to be taken as 10 metres/s while moving between the coordinates (50000,0,10) metres and (68000,0,10) metres. Following pre decided simulation parameters the minimum ergodic achievable rate is compared for various approaches, for a period as shown in the figure.

The rate is compared between shore-based MCN and the UAV hybrid MCN. For the shore/TBS based MCN the CSI procured is accurate, while for the UAV hybrid MCN the

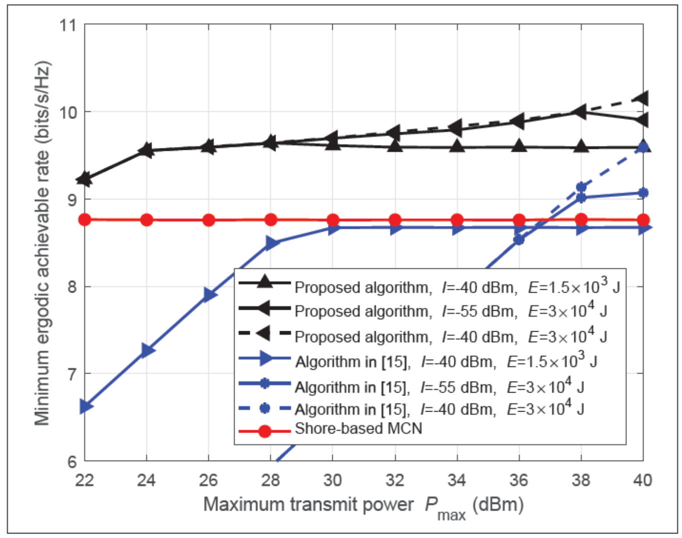

Fig. 5: Minimum Ergodic Rate Achievable in Multiple Algorithms

CSI is inaccurate and the backhaul capacity has a limit. Even still the performance of the hybrid MCN can be improved by using the UAV thus decreasing the distance of transmission to the user vessel.

We can also note here that applying the scheduling methods for terrestrial UAVs directly on the ocean will be inefficient due to different constraints, maximum transmit power, interference and large scale CSI. We can also see that the performance depends on backhaul capacity limitations and residual energy constraints from the part in the graph in Figure 5 where P-max exceeds 28 dBm, E is 1500 Joules and 'l' is -40 dBm. In this part if we increase the P-max, the performance doesn't change. Apart from this we can see in the region of the graph in Figure 5 where P-max exceeds 38 dBm and E is 30000 Joules that the interference constraint's result can be noticed. Finally when 'l' is increased, there is an increase in the performance and the specifically designed maritime algorithm [15] gives the best performance by only utilizing large scale CSI.

VII. Conclusions

We have seen in this paper, the upsurge in need for maritime broadband networks and the various related works which have tried to solve the problem. We have also seen their limitations and drawbacks. To provide a base for studying the hybrid MCN we have looked into the TBSs, Maritime Satellites and UAVs individually. Establishing a robust hybrid network requires a careful study of the marine users and vessels from collected data as well as their unique characteristics which we have done in the paper. We have seen how UAVs distinguish themselves from other components of a MCN by providing on-demand network coverage through its mobile agility and by scheduling and deploying the UAVs dynamically. We have also studied the various challenges faced upon integrating UAVs into existing MCNs and their solutions in detail. Finally we have analysed a case study to illustrate the advantages of using the satellite-UAV-TBS hybrid network.

VIII. Personal Findings, Insights and Ideas

I believe a solution to the ever growing need for the most effective maritime broadband network connection can be the *Starlink Satellite Constellation* developed by SpaceX combined with Unmanned Aerial Vehicles.

As of June 2021, SpaceX has already launched 1730 Starlink Satellites and will be sending more in the upcoming months, thus will form well connected satellite clusters around the Earth. It has been reported that with the use of Starlink broadband users at Sea will be able to get network with low latencies and high internet speeds as well.

This is due to the sparse distribution of users and thus these users will connect directly to the satellites orbiting the Earth without the need for terrestrial base stations. The satellites aim to provide an unbelievable speed of 1 Gigabit/s in contrast to the current maximum limit of a few hundred Mb/s on the ocean [16].

To exploit it to the maximum, dual parabolic antennas would be used to track the satellites. Starlink satellites consist of inter satellite laser links which means the satellites can send and receive data and communicate between each other thus creating a complete link between a ground base station and a user vessel far off in the ocean. Crosslinks [17] will be critical in solving the problem by passing the signal off to another satellite in the constellation, which would keep passing it until it reaches a satellite within sight of a TBS. Some parts of this crosslink technology have been deployed by Iridium in its infrastructure quite recently as well.

On the other hand, to complete the MCN and for robustness, UAVs will be used as they provide agile mobility in places of limited reach and for flexibility. *Thus I think with this proposed solution we will be nearer to realizing the goal of maritime networks supporting 5G network on the ocean.*

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