A HYBRID SATELLITE-CELLULAR COMMUNICATIONS TERMINAL FOR CONNECTED AND AUTONOMOUS VEHICLES

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I | INTRODUCTION

Two distinct models for the architecture of autonomous vehicles (AVs) have emerged. One is for a self-contained, mostly unconnected car, with all sensors and crucial systems onboard that only exchanges data with the Internet when necessary. The other model represents an always-connected vehicle that relies heavily on the computing power and real-time driving experience of other vehicles provided by the cloud. It's likely that most AVs will fall somewhere between these two extremes, and the decision about the degree of reliance on the Internet will be influenced by such considerations as safety, security, and cost.

However, there is no doubt that all AVs will be powerful computer systems. The Automotive Edge Computing Consortium (AECC) makes 3 significant observations regarding the demands of the connected vehicle [1]:

1. Connected vehicles will generate around US$150B in annual revenue.
2. The number of connected vehicles will grow to around 100M globally.
3. The data volume transmitted between vehicles and the cloud will be around 100 petabytes per month.

In a future with connected vehicles, the data traffic will be vast, and new network infrastructures and computing architectures will be needed for processing and storage.

Vehicles will generate and consume data in various scenarios such as vehicle to everything (V2X), the vehicle as a living room for infotainment and e-commerce, and autonomous driving. To support these scenarios, reliable and ubiquitous connectivity is essential. A common approach to vehicle connectivity is to integrate modems and modules that interface with existing terrestrial networks, such as the 4th Generation Long Term Evolution (4G LTE) network or an emerging 5th Generation (5G) network. When coverage is sufficient, and the network is uncongested, performance is generally adequate. However, it is projected that by 2020 only 63% of the world's population and 37% of the landmass will be covered by LTE [2].

To achieve fully-global and high-throughput coverage, Kymeta proposes a hybrid connectivity solution whereby fixed terrestrial networks are supplemented with high-throughput satellite access technologies. This white paper demonstrates the implementation and testing of a hybrid satellite-cellular terminal for connected and autonomous vehicles. The terminal design leverages recent advances in holographic and diffractive metasurface antennas to implement an electronically scanned, high-gain satellite antenna that is commensurate with the size, weight, power, and cost requirements of the general consumer automobile. Kymeta demonstrates that with the proposed hybrid terminal the connected vehicle can maintain contact with the public data network through either the terrestrial cellular link, or the satellite link, with automatic switching and traffic shaping based on link performance metrics.

2 | SYSTEM ARCHITECTURE

2.1 | HYBRID NETWORK

Hybrid connectivity uses multi-access technology routing to provide the optimal independent or aggregated connection from a source, such as an edge router, to a destination (i.e., a public data network such as the Internet). When a router is connected to multiple access technologies at once, for example, an active LTE connection and an active satellite connection, one approach to providing continuous connectivity is to apply routing logic to switch traffic between the available transport networks based on a given or learned set of conditions. In this scenario, there is always one active transport network and a single (or multiple) dormant transport network(s) as both cannot be used simultaneously.

The overall benefit to this approach is that users or platforms connected to the edge router can access content from other users and platforms on public data networks through multiple different or aggregated access technologies (e.g., LTE, 5G, satellite) as shown in Figure 1.

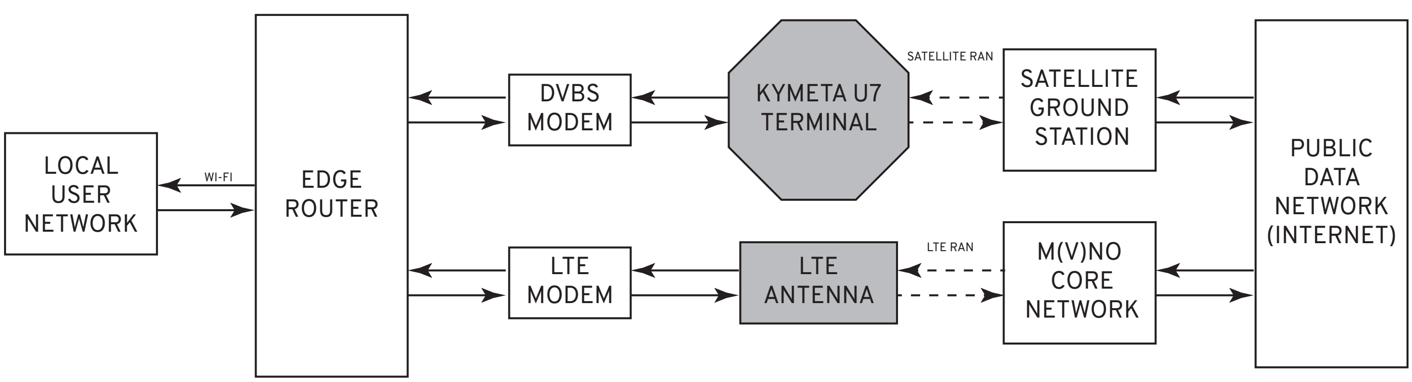

FIG. 1. HYBRID NETWORK WITH NEARBY USERS.

This approach also greatly reduces the complexity in connecting user devices over multiple different access technologies. In the hybrid connectivity system, local users connect to the edge router over a standard interface such as IEEE 802.11-based Wi-Fi or direct Ethernet as shown in Figure 1.

As the device maintains a connection to the router, protocols within the router determine the best access technologies to attach to the internet. If the users are not co-located with the edge router, then other technologies such as IP mesh networking or LTE small cells can be connected to extend the network from the edge router.

2.2 | SATELLITE ARCHITECTURE

The typical user equipment required to establish a high-throughput satellite link to a moving platform is comprised of a gimbaled dish antenna. This type of user terminal works well on large ocean vessels and communications on the pause (COTP) applications (e.g. satellite news gathering on large trucks or vans) but is extremely impractical when considering the requirements of the general consumer automobile.

Kymeta has recently commercialized a novel, electronically scanned, flat-panel satellite antenna technology, as reported in [3], to address general automotive requirements. Kymeta technology is based on a dynamically reconfigurable, diffractive metasurface, where high-birefringence liquid crystal is used as a tunable dielectric. The use of liquid crystal permits highly-scalable manufacturing leveraging the capital investments made in the liquid crystal display industry. The diffractive metasurface approach, possesses significant performance advances over phased array approaches, including:

- Interleaved receive and transmit arrays permitting full duplex operation from a single physical aperture
- Electronically adjustable polarization from tracking linear to circular (RHCP and LHCP)
- Full 360° azimuth scanning and elevation scanning below 15° with return loss independent of scan angle
- FCC- and ITU-compliant pointing accuracy with platform motion up to 30 degrees per second

A schematic block diagram of the satellite terminal is shown in Figure 2, where the Kymeta u7 antenna is comprised of a 70 cm diffractive active aperture [3].

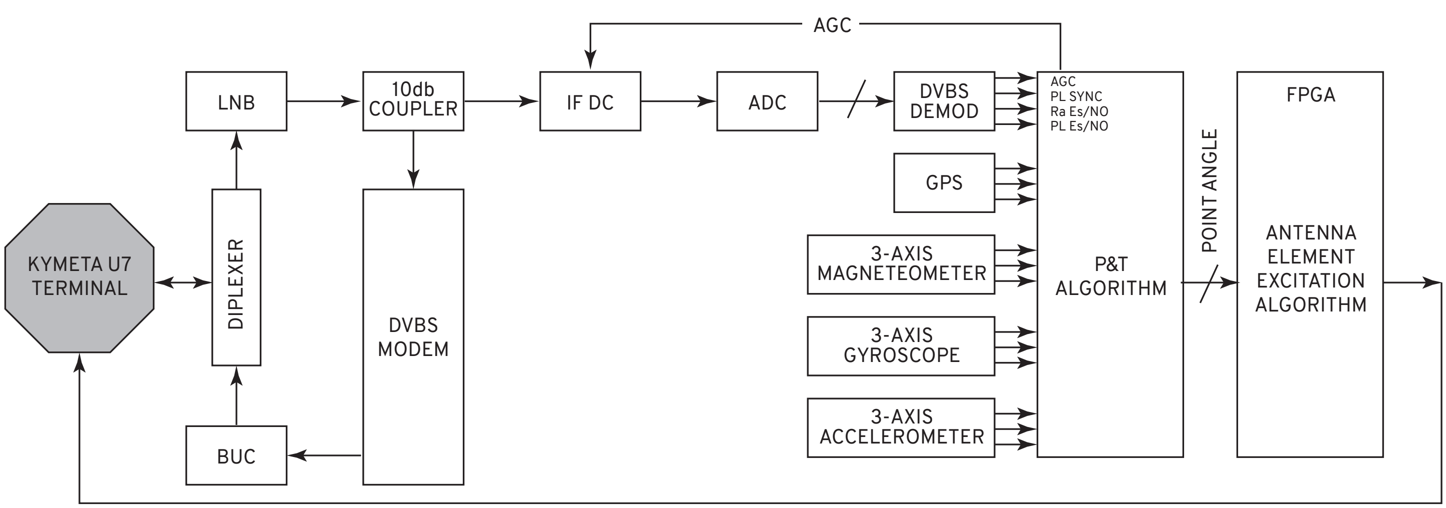

FIG. 2. BLOCK DIAGRAM OF THE SATELLITE PORTION OF THE HYBRID TERMINAL

Table 1 provides examples of the satellite industry migration from high-throughput, geostationary (GEO) satellites, to mid-Earth orbit (MEO) constellations and low-Earth orbit (LEO) constellations. As the altitude decreases, satellite size and power consumption reduce commensurately with improved path loss. With dense LEO constellations, such as those proposed by OneWeb and SpaceX, truly global coverage can be achieved.

TABLE 1. REPRESENTATIVE SATELLITE CONSTELLATIONS

CONSTELLATION	ALTITUDE	CAPACITY	# SATELLITES
Intelsat Epic^{NG} [4]	35,786 Km GEO	25-60 Gbps/ satellite	6
O3B mPower [5]	8,062 Km MEO	~1.5 Tbps/satellite	42
OneWeb [6]	1,200 Km LEO	10 Gbps/satellite	600
SpaceX Starlink [7]	550-1,110 Km LEO	20 Gbps/satellite	4,425

The diffractive metasurface approach provides a flexible solution as satellite networks evolve from high-throughput, GEO-HTS, MEO, and LEO satellite constellations. Apertures as small as 20 cm in diameter can deliver > 100 Mbps throughput when paired with the appropriate LEO satellite constellation [3].

3 | IMPLEMENTATION AND RESULTS

Kymeta's hybrid connectivity system is currently being implemented in multiple phases. Initially, switching decisions are made based on link performance metrics in a static failover mode. The next phase implements software-defined, wide area network (SD-WAN) traffic shaping and steering based on content and data type. Future development efforts will take the SD-WAN approach further by implementing deep learning and artificial intelligence for situation-based routing. The concluding phase of this effort is full integration with the 5G network.

3.1 | PHASE 1: STATIC FAILOVER

Currently implemented, static failover uses a static ruleset to determine the active transport network. This can be based on several factors related to link performance (e.g., latency, packet loss, jitter, etc.). In this condition, a network administrator sets conditions for each transport link as different access technologies may not directly compare. For example, packet latency in an LTE network of above 500ms may indicate a poorly performing network whereas 500ms of packet latency in a geostationary satellite network is a best-case condition.

When configured, an ordered priority list is established. As an active priority network degrades to a point below a threshold, it will failover to the next available link. At this point, the high priority active transport network becomes dormant and the next priority transport network becomes the active network. When the performance of the dormant priority link increases above the threshold, it once again becomes the active link.

FIG. 3. TEST VEHICLE WITH RECONFIGURABLE METASURFACE ANTENNA MOUNTED TO THE ROOF

We demonstrated this configuration in October of 2018 in the southern desert of the United States. The demonstration originated in an urban environment with a reliable LTE network and transitioned to a remote portion of the desert with no available LTE network. Figure 3 shows the test vehicle with satellite antenna on the roof.

We determined connectivity using an ICMP ping test to a public internet server (8.8.8.8) at a 1000 ms interval, and we measured two test events. In the first event, we biased the edge router to use the LTE network as the active transport when it was available. When the LTE network was no longer available due to lack of coverage, the router switched to satellite as the backhaul method. This resulted in overall network connectivity of 97.96% as depicted in Figure 4.

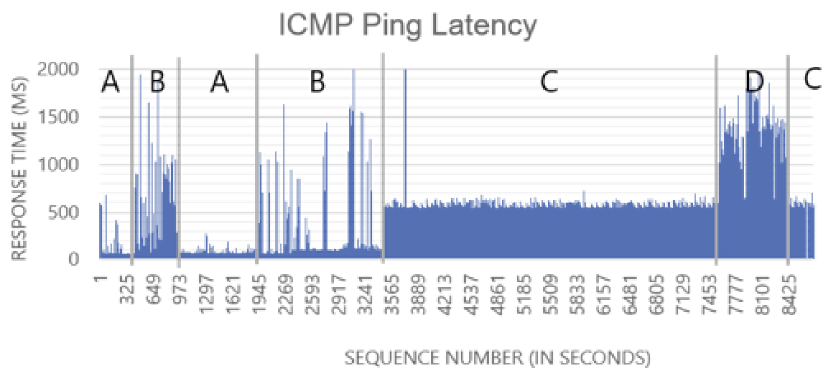

FIGURE 4. ICMP PING LATENCY FOR TEST CONDITION 1. SECTION A REPRESENTS NORMAL LTE TRAFFIC. SECTION B IS NOISY OR DEGRADED LTE TRAFFIC. SECTION C REPRESENTS TRAFFIC OVER SATELLITE. SECTION D REPRESENTS TRAFFIC OVER SATELLITE AND MESH NETWORK.

In the second test event, the edge router was configured to bias toward satellite as the active transport link with LTE as the backup transport. This resulted in overall network connectivity of 99.03% as depicted in figure 5 below.

In both test events, the active transport network can be inferred based on the ping response time. The LTE network in this event had ping times of less than 100ms. The satellite network had ping times between 500ms and 700ms. For portions of the test, the measurement device was directly connected to the edge router via Wi-Fi as depicted in figure 1. For other portions of the test, the measurement device was connected over a long-range mesh network, which was approximately 1 km away from the edge router. There are outliers in the test data which are the result of corrupted ICMP packets that arrived much later than the threshold times.

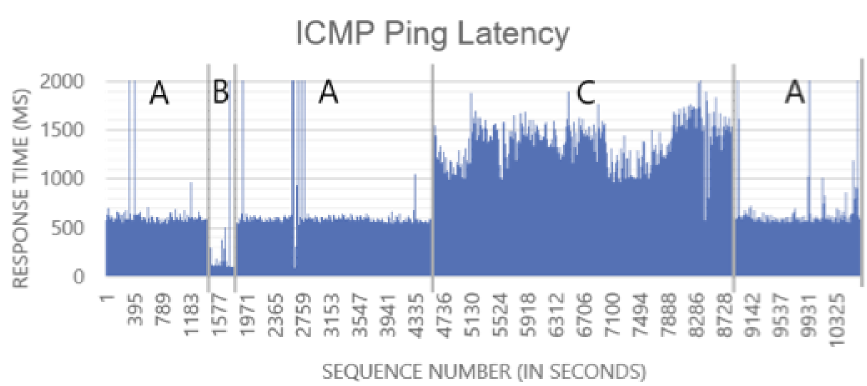

FIGURE 5. ICMP PING LATENCY FOR TEST CONDITION 2. SECTION A REPRESENTS NORMAL SATCOM TRAFFIC. SECTION B REPRESENTS TRAFFIC ON THE LTE NETWORK DUE TO SATELLITE OUTAGE. SECTION C REPRESENTS TRAFFIC FROM A MESH NETWORK DEVICE.

During the satellite sessions, we demonstrated a link of 6 Mbps down/3 Mbps up. This performance was limited by the GEO satellite network and modem employed. As noted in section 3.2, advanced satellite constellations can extend link throughput beyond 100 Mbps down.

The data shows a stable network connection during the duration of both test events, regardless of the condition of either the LTE or satellite network. The losses in connectivity, though limited, occur when the network switches from one active transport to another. While the effects of this will be negligible in some cases such as internet browsing, file transfer, or streaming buffered media, it will present as a network drop during real-time services such as voice over Wi-Fi (VoWIFI) or voice over IP (VoIP) calls, video calls, or traffic requiring a secure session. These shortcomings will be addressed in the second phase.

3.2 | PHASE 2: SD-WAN

Kymeta is currently extending the failover approach to an SD-WAN based hybrid solution. This approach uses an edge router with SD-WAN logic built in to perform several functions. The first is a quality of service (QoS) approach to delivering traffic over multiple networks. The logic in the router identifies the traffic demand (i.e., type of content) and determines the best available transport network for which to route that specific traffic. Different types of content may be near-simultaneously routed over multiple different transport networks. This requires a layer of orchestration which will reside in the edge router.

Building on the dynamic QoS approach, another routing methodology can be used which takes other factors such as subscription and service cost into the decision logic. Kymeta has defined this approach as best-cost routing. Best-cost routing includes the dynamic traffic steering logic of the SD-WAN and incorporates a layer of service cost. If the cost per bit of satellite traffic is higher than the cost per bit of LTE traffic, the routing logic will steer the traffic toward the lowest cost platform. As these costs are dynamic, the hybrid system is fully integrated into Kymeta's service and support back end so that there is a continuous input from the Kymeta service infrastructure into the router logic.

The hybrid connectivity solution is currently under development. This includes a robust and iterative test and evaluation phase. The results of that testing will be documented in Q3 2019 and will focus on overall quality of experience (QoE) for the end user as defined in table 2 below.

TABLE 2. QoE EVALUATION PARAMETERS

QoE.1	**Network switching time between the active and dormant transport network**
QoE.2	Data session continuity across transport network switch event
QoE.3	Data utilization on congested networks

QoE.4	Active transport selection in varying link conditions
QoE.5	Overall user network up time/overall backhaul connection up time

The measurements of the above metrics will be conducted initially in an instrumented lab environment. Network analysis tools will be utilized to determine total time for network switching as a method of determining optimized configurations. Sessions will be initialized from user devices to locations on public data networks to measure session continuity as the active transport network switches from one network to another. Additionally, network congestion testing will be conducted to observe traffic shaping and offloading during a congestion event. Finally, service level agreement type metrics will be measured. These will be measured in a dynamic environment including drive tests in several different locations.

This report will include the test results from the SD-WAN implementation.

4 | FUTURE DIRECTION

Future development efforts for the hybrid network will leverage artificial intelligence (AI) and integration with 5G networks. That work will be conducted in two phases.

4.1 | FUTURE DEVELOPMENT PHASE 1: DEEP LEARNING AND AI

The incorporation of machine learning logic, such as deep learning and artificial intelligence (AI), in conjunction with the edge compute infrastructure integrated into the hybrid connectivity platform, will allow the system to learn specific network conditions as they occur. This will enable routing decisions to be made proactively rather than reactively. As edge compute and communications infrastructure is implemented, the pathways for sharing, storing, and retrieving information across platforms is greatly increased. This will result in a large dataset for the edge routers to be able to make routing decisions based on learned information.

4.2 | FUTURE DEVELOPMENT PHASE 2: 5G AND TERRESTRIAL NETWORK INTEGRATION

Finally, as communications progress toward the 5G standard, the satellite hybrid network architecture plays a significant role in ensuring continued communications. A mobile, satellite-based radio access network (RAN) delivers information on a 5G waveform like the way information is delivered across a terrestrial RAN as depicted in Figure 3 [8].

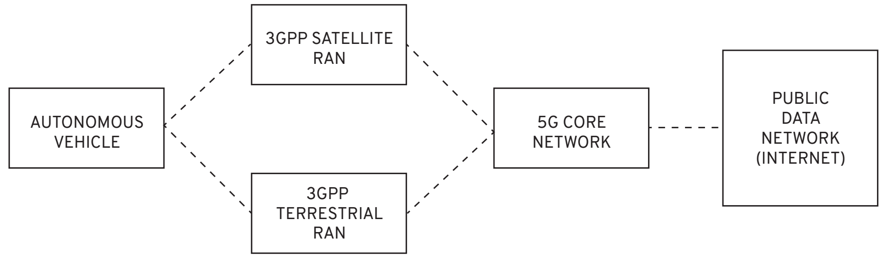

FIG. 6. CONNECTIVITY ARCHITECTURE WITH TERRESTRIAL AND SATELLITE RANS.

The network originates from the same core functions so the terrestrial RAN and satellite RAN are simply different access technologies on the same network. Network function virtualization and other network slicing technologies can direct different types of traffic with different performance requirements across the different transport networks when multiple are available.

5 | CONCLUSION

Kymeta has developed and demonstrated a hybrid satellite-cellular network system to provide ubiquitous, reliable, and robust coverage for connected vehicles. Using our high-throughput satellite communications terminal in combination with terrestrial LTE and other wireless networks, we demonstrated failover switching from LTE to satellite, and achieved 6 Mbps down/3 Mbps up over the satellite link in a remote part of the southwest United States.

Our hybrid terminal concept solves critical problems caused by relying on only a single network for coverage. The satellite portion of the terminal is flexible and will scale to throughputs > 100 Mbps as next-generation satellite constellations come on-line. By enabling an edge router to determine the optimal transport network given a dynamic set of parameters, this system will provide automobile manufacturers and other integrators with the ability to offer constant connectivity in virtually any environment.

6 | REFERENCES

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