hellaPHY® Location

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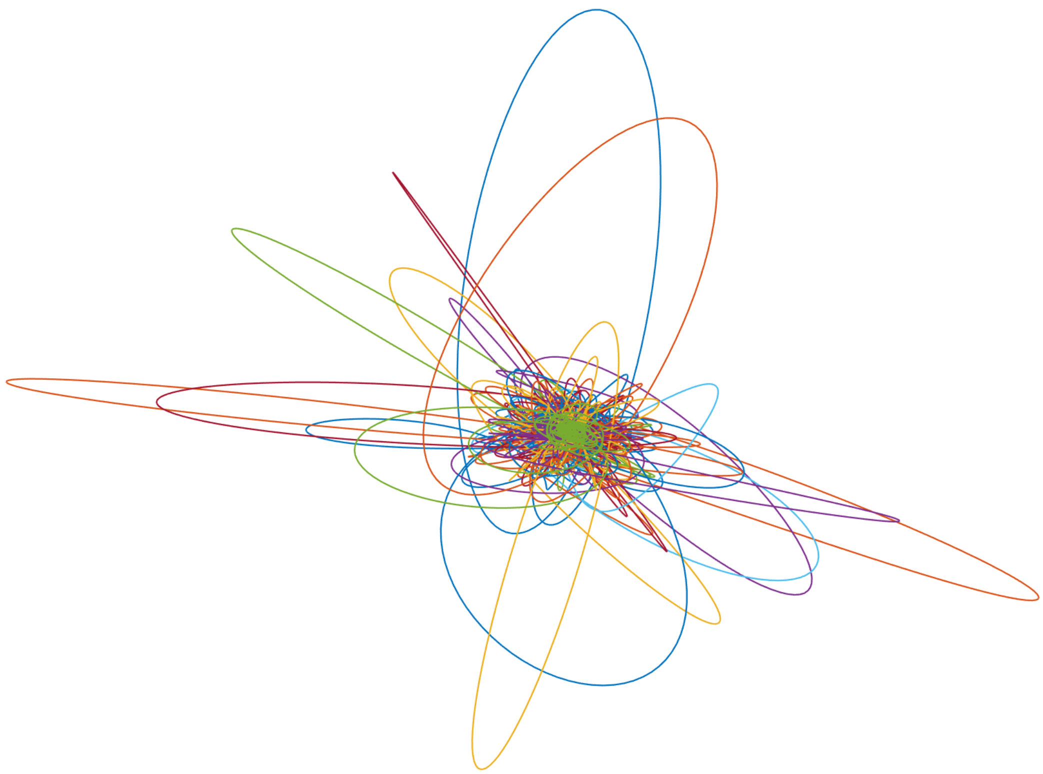

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Executive Summary

hellaPHY® Location from PHY Wireless enables new location-based applications and services by dramatically extending device battery life.

To achieve both data communications and positioning an existing Internet of Things (IoT) wireless device might use an LTE modem for data, GPS for outdoor location, and WiFi for indoor location. An IoT device with hellaPHY® Location software eliminates the need for GPS and WiFi. Instead, positioning is performed using existing LTE signals. The reduction of components reduces cost, shrinks device size, and improves battery life.

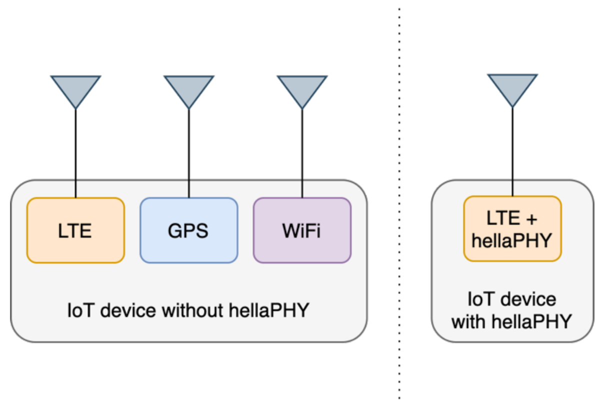

Figure 1: hellaPHY® Location eliminates components, reducing cost and size and improving battery life.

hellaPHY® Location thus brings the power and scale of 4G-LTE cellular networks to the problem of the Location of Things (LoT). This offers an effective, low-cost solution for IoT applications.

hellaPHY® Location leverages existing downlink 4G-LTE positioning reference signals (PRS) as standardized by 3GPP Release 9. These terrestrial signals are typically 50dB more powerful than satellite GPS signals, offering a fast and efficient positioning fix for both indoor and outdoor applications.

hellaPHY® Location requires minimal interaction with the network, reducing congestion and extending the battery life of the device. It performs cell time-of-arrival (TOA) estimation and position estimation on the device with advanced algorithms designed to combat degrading effects of multipath and interference found in cellular environments. Supporting the hellaPHY® Location protocol on the device is simple. It runs on an ARM processor, requiring only 6MHz of CPU bandwidth during a positioning session. The memory required is less than 100kB, and that is 1% to 2% the requirement for the standard LPP/SUPL protocol [1, 2, 3].

hellaPHY® performs a position fix quickly consuming minimal power. The cumulative effects have a dramatic impact on battery life as seen in Figure 2. In a geofencing application, a GPS-based device is expected to have a battery life of 14.7 days, while a device using cloud-based cellular positioning extends the battery life to 19.5 days. The battery life of the hellaPHY® device is increased dramatically to 4 years: 100x better than the GPS device. For a breadcrumbing use case the hellaPHY® device has a 67x gain over the GPS device with an 8 year battery life.

This dramatic improvement to battery life enables new location-based applications and services. The remainder of this white paper examines the hellaPHY® Location system architecture, describes use cases, and provides a battery life analysis.

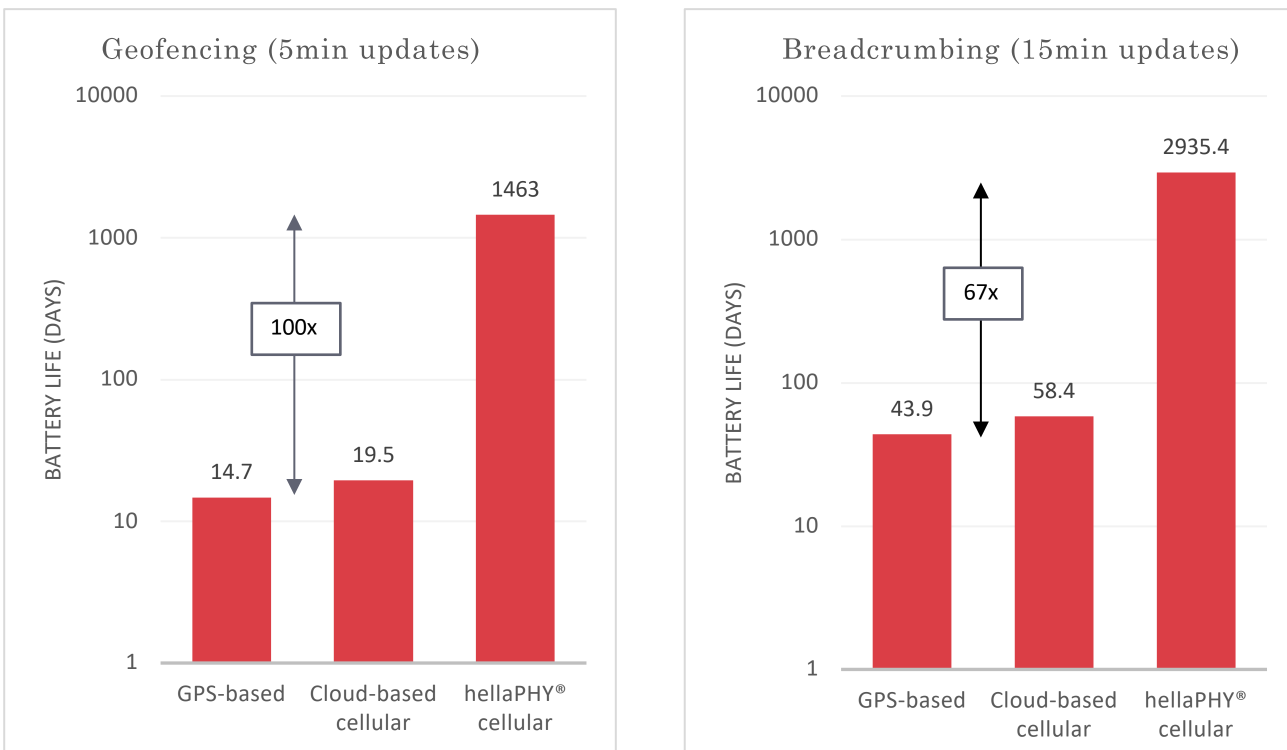

Figure 2: hellaPHY® Location dramatically extends battery life for geofencing and breadcrumbing applications.

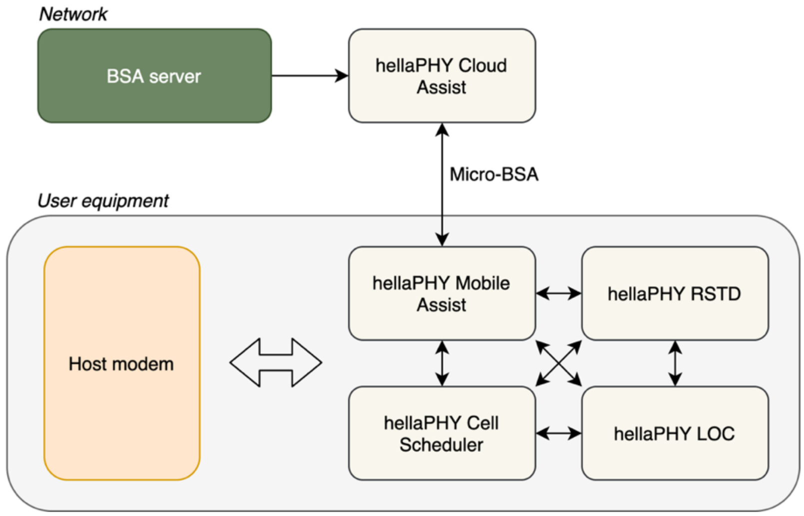

Figure 3: hellaPHY® Location system architecture.

System Architecture

The hellaPHY® Location system architecture is shown in Figure 3. The mobile network operator (MNO) base station almanac (BSA) database contains the cell parameters defining the network layout. Each cell in the database is characterized by a unique cell identifier (ECGI), a latitude and longitude of the cell transmission point, a physical cell index (PCI), antenna aperture and orientation details, transmission power, and various other parameters. The **hellaPHY® Cloud Assist** server interacts with the BSA database to provide the hellaPHY® device (user equipment, or UE) with a small subset of the operator BSA. This *micro-BSA* may consist of several hundred cells close to the serving cell of the UE. The required parameters per cell can be fit into about 120 bits, so a 1000 cell micro-BSA can be expressed by

$$1000 \text{ cells} \times 120 \text{ bits/cell} \times 1 \text{ kB}/8000 \text{ bits} = 15 \text{ kB}.$$

This 15kB 1000-cell micro-BSA is transferred to the UE in a few seconds over the wireless link while the device is in LTE connected mode. A smaller micro-BSA can be requested for shorter download times and less storage, and a larger micro-BSA can be requested for greater coverage and less overall interaction with the network. As a point of reference, for a typical cell density of 1 cell/km^2, a 1000-cell micro-BSA provides coverage for a 1000 km^2 area. With a single micro-BSA many position fixes can be obtained. Therefore, once the micro-BSA is downloaded the device requires minimal additional interaction with the network.

The **host modem** provides the onboard hellaPHY® software with PRS occasion subframes. A typical PRS deployment is 1ms of PRS every 160ms. So about 6 PRS occasions per second.

Across a typical 5 second positioning event, around 30 PRS occasions are captured and fed to hellaPHY®. For extended battery life, the PRS capture is performed in low power LTE eDRX idle mode or LTE power save mode (PSM).

The **hellaPHY® Cell Scheduler** dynamically determines cells from the micro-BSA to perform measurements for optimal location accuracy with low complexity. **hellaPHY® RSTD** performs the measurements using advanced TOA and filtering algorithms. **hellaPHY® LOC** is comprised of position estimation algorithms that process the TOA measurements and various quality metrics to arrive at an estimate of the UE location. These components are tightly coupled for rapid and efficient derivation of accurate position estimates in challenging cellular environments.

Comparative Analysis

hellaPHY® Location is now compared to two other solutions for low-power wide-area (LPWA) IoT applications. See Table 1 and Figure 4.

Table 1: Comparative analysis of three LPWA devices.

Parameter	**Device A**	**Device B**	**Device C**
Data connectivity	LTE-M	LTE-M	LTE-M
3GPP Category	M1	M1	M1
Location technology	Assisted GPS	Cloud-based cellular	hellaPHY® Location
Location measurement signals	Satellite	Terrestrial LTE	Terrestrial LTE
PRS density	N/A	1ms every 160ms	1ms every 160ms
Position calculation placement	On device (UE-based)	On cloud server (UE-assisted)	On device (UE-based)
Cloud assistance	Yes (ie, LPP/SUPL)	Yes (ie, LPP/SUPL, or other)	Yes (hellaPHY® Cloud Assist)
Outdoor accuracy (nominal, meters)	5	>100	50
Indoor accuracy (nominal, meters)	N/A	>100	50
Battery	AA, 2350mAh	AA, 2350mAh	AA, 2350mAh

Each of these devices employ a 3GPP Category M1 (LTE-M) baseband for data connectivity on a cellular network. LTE-M low power features include power save mode (PSM) and RRC Idle discontinuous reception (DRX). In this analysis, it is assumed the PSM nominally draws 0.01mA and RRC Idle DRX nominally draws 2mA [4]. When actively connected to the LTE network exchanging data in RRC Connected mode it is assumed the LTE-M modem draws 150mA [4].

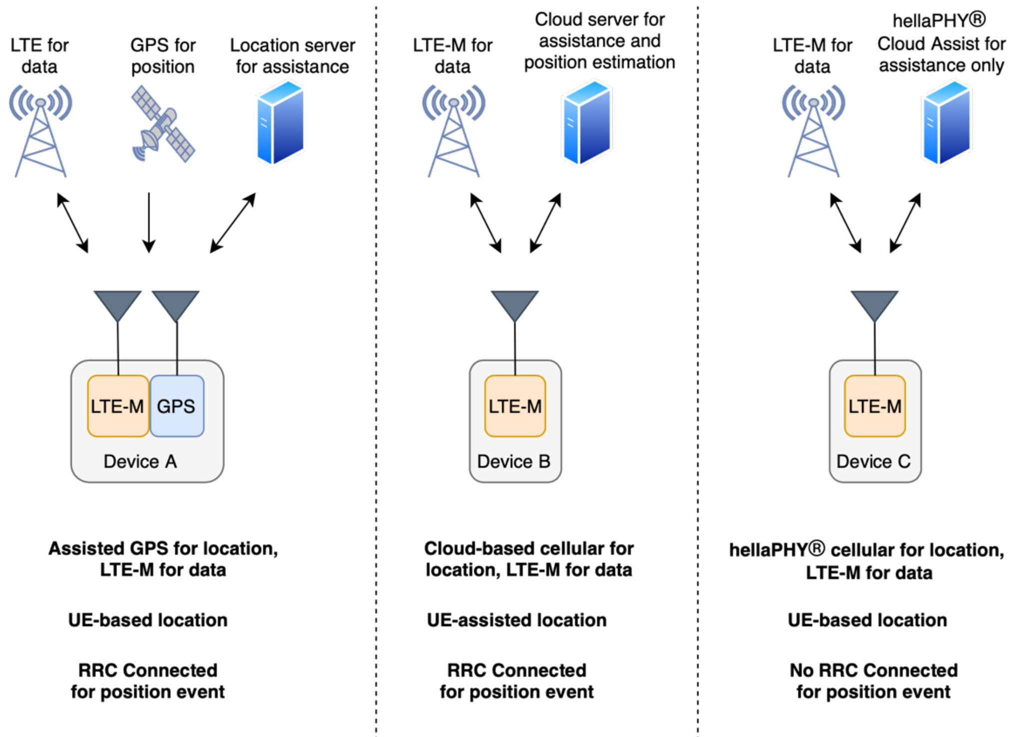

Figure 4: Three devices studied.

In terms of location technology, Device A uses assisted GPS (A-GPS), Device B uses some type of cellular cloud-based solution, and Device C use hellaPHY®. Device A performs measurements on satellite transmissions and Devices B and C perform measurements on terrestrial LTE cellular signals. Devices B and C make use of 1ms of PRS transmitted every 160ms, and possibly common reference signals (CRS). Higher density PRS is allowed in the 3GPP specification, but it is assumed the mobile network operator is deploying this low density PRS to prioritize data capacity.

Device A performs the position estimate on the device, in the GPS receiver. The GPS receiver is highly optimized in its timing measurements, position calculation updates, and filtering. This tight coupling between algorithms results in an accurate position accuracy.

Device B perform measurements on the device and uploads these measurements to the cloud server where the position estimate is performed. This method has a few fundamental issues:

- Uploading the position measurements is costly in terms of power drain, shortening battery life.
- Separating the position measurements (on the device) from the position calculation (in the cloud) can degrade performance. The cloud may have large amounts of computing capacity, but uploading measurement at a high rate (like every new PRS occasion) to the position calculation may not be feasible thus limiting performance.

- Dividing algorithm responsibility between multiple vendors can lead to suboptimal outcomes. For example, in 3GPP UE-assisted OTDOA, one vendor may be responsible for the UE RSTD algorithm passing 3GPP minimum conformance, while another vendor is responsible for the location server assistance data and position calculation. The overall position accuracy is difficult to manage for the MNO with this division of responsibility.
- Security. Storing the location information of many (millions or billions) of devices in the cloud invites bad actors.

Device C overcomes the issues with Device B by using hellaPHY® UE-based location. The interplay between the measurements, the position calculation updates, and filtering improve location accuracy in an efficient manner. Keeping the device location on the device provides a security enhancement.

In terms of expected location accuracy, A-GPS remains the gold standard for outdoor location where the device has clear visibility of the sky (satellites). A nominal accuracy of 5m is expected. On the other hand, indoor coverage for A-GPS is limited and for the purpose of this analysis is assumed to not be available. Device B is expected to have nominal position accuracy of >100m both indoor and outdoor. This solution is obviously not as accurate as outdoor A-GPS, but considered useable for many IoT applications and has the benefit of indoor coverage.

Device C is expected to have a performance better than Device B with a nominal accuracy of 50m. This expected performance advantage is based on recent trial results from a Tier-1 MNO who compared hellaPHY® on Cat-M1 with a commercial deployment of UE-assisted OTDOA/ECID on a Cat-1 UE. Through on-network live testing across a diverse set of locations (indoor/outdoor, dense urban/suburban/rural) hellaPHY® on the low-end Cat-M1 UE outperformed the higher-end Cat-1 device.

The nominal accuracy of 50m on the hellaPHY® Device C is still not as accurate as the outdoor A-GPS Device A. This is due to the higher levels of multipath and non-line-of-sight (NLOS) distortion present in the LTE terrestrial signals compared to the mostly light-of-sight (LOS) reception of the satellite signals in the GPS receiver. However, the hellaPHY® Device C does have the advantage of indoor and outdoor coverage, and offers a significant advantage in terms of battery life as analyzed next.

Geofencing

To analyze expected battery life, use cases are to be defined. The first example considered is the application of geofencing as illustrated in Figure 4. The user defines a bounded area (green) where an asset is to reside. If and when the asset roams beyond the bounded region, the user is alerted. The asset might be a pet at a home, a valuable tool on a jobsite, or a bike in a bike sharing system on a campus.

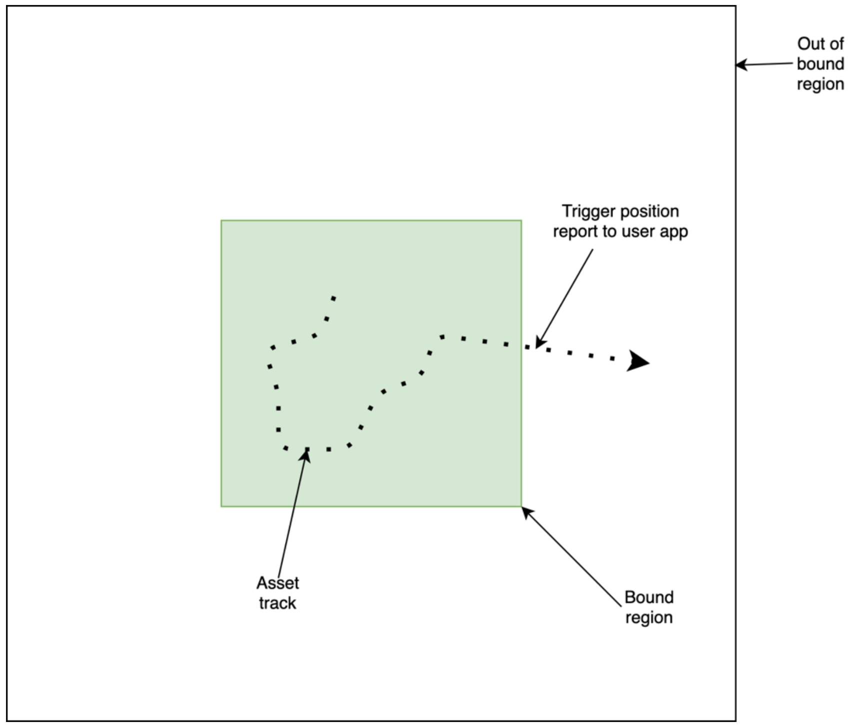

Figure 4: Geofencing application.

For this geofencing use case, suppose each device estimates the asset location once every 5 minutes, and the asset roams outside of the bounded area once per two weeks.

Table 2 shows the battery life analysis for the three devices with a single 2350mAh AA battery. Notice that each device spends the vast majority of its time (>95%) in PSM, consuming a nominal 0.01mA [4]. It is the small fraction of the time (<5%) outside of PSM where the three devices differ and where battery life is affected.

For the A-GPS device, the analysis assumes a new position fix requires 10s in RRC Connected mode where the LTE modem draws 150mA [4] and the GPS receiver draws 50mA [5]. For this device, the location is estimated locally. When the asset roams beyond the bounded area the position estimate is upload to a user app consuming 2s of RRC Connected mode. Notice that the position event lasts only 3.33% of the device life but consumes 99.85% of the battery. The battery life is estimated to be 14.7 days.

Next consider Device B. Every 5 minutes it enters RRC Connected mode to provide 10s worth of measurements to the cloud server. The measurements may be over LPP/SUPL using OTDOA or E-CID, or some other cloud-based solution. The measurements are used by a cloud server to estimate the asset location. Since the location is estimated off-device Device B is not tasked with reporting the asset location when it leaves the bounded area. The battery life of Device B is estimated to be 19.5 days: a 33% gain over the A-GPS device. The gain is attributed to the LTE-only operation during the positioning event with no additional drain from the GPS receiver.

Now consider Device C. Once a week the hellaPHY® device retrieves an updated 1000-cell micro-BSA, requiring 2.4s of RRC Connected mode. Once every 5 minutes the device obtains an updated position estimate. The hellaPHY® position estimate is done quickly, in 5s, in a 3.375mA low-power mode. This low-power operation assumes 2mA for the LTE modem (similar to a nominal LTE Idle DRX drain) and accounts for 6MHz of processing in an ARM MCU with a 50% margin [4, 6]. It is assumed that hellaPHY® can obtain a position fix faster (5s versus 10s) since it has the needed assistance data available in the micro-BSA.

The estimated battery life for Device C extends to 1463 days: 100x better than the A-GPS device. This gain is due to the low-power mode of performing a position fix. During an updated position estimate the device requires no interaction with the network, and the accumulated impact of this feature results in a device with many-year battery life on a 2350mAh AA battery.

Table 2: Battery life analysis for a geofence use case.

Geofencing with 5 minute position updates. Out-of-bound region triggering once every two weeks.				
Position update rate (min)	5			
Battery capacity (mAh)	2350			
Device A: A-GPS for location, LTE-M for data				
	PSM (Note 1)	A-GPS with LPP/SUPL in RRC Connected (Note 2)	Report location in RRC Connected (Note 3)	
Duration (s)	83520	10	2	
Average current (mA)	0.010	200.000	150.000	
Times per day	1	288	0.071	
Total time per day (s)	83520	2880	0.143	
Percent of total	96.67%	3.33%	0.00%	
Total mAh used per day	0.232	160.000	0.006	
Percent of total	0.14%	99.85%	0.00%	
Total mAh used per day	160.238			
Battery life (days)	14.7			
Device B: Cloud cellular for location, LTE-M for data				
	PSM (Note 1)	Cloud-based in RRC Connected (Note 4)		
Duration (s)	83520	10		

Average current (mA)	0.010	150.000		
Times per day	1	288		
Total time per day (s)	83520	2880		
Percent of total	96.67%	3.33%		
Total mAh used per day	0.232	120.000		
Percent of total	0.19%	99.81%		
Total mAh used per day	120.232			
Battery life (days)	19.5			
Device C: hellaPHY® cellular for location, LTE-M for data				
	PSM (Note 1)	hellaPHY® in low power mode (Note 5)	Report location in RRC Connected (Note 3)	hellaPHY® micro-BSA update in RRC Connected (Note 6)
Duration (s)	84960	5	2	2.4
Average current (mA)	0.010	3.375	150.000	150.000
Times per day	1	288	0.071	0.143
Total time per day (s)	84960	1440	0.143	0.343
Percent of total	98.33%	1.67%	0.00%	0.00%
Total mAh used per day	0.236	1.350	0.006	0.014
Percent of total	14.69%	84.05%	0.37%	0.89%
Total mAh used per day	1.606			
Battery life (days)	1463.0			
Note 1: Assuming a nominal 10uA for PSM [1].				
Note 2: Assisted GPS with LPP/SUPL in RRC Connected assumes 150mA for LTE modem [4] and 50mA for GPS receiver [5].				
Note 3: For UE-based location it is assumed 2s of RRC Connected mode at 150mA [4] to upload location estimate.				
Note 4: For UE-assisted location it is assumed the device reports measurements to cloud server with 10s of RRC Connected mode at 150mA [4].				
Note 5: hellaPHY® in low power mode assumes a power consumption similar to RRC Idle DRX of 2mA [4] plus 6MHz 1.2v Cortex M4 at 50uW/MHz [6] plus 50% overall margin.				
Note 6: hellaPHY® micro-BSA update assumes almanac information of 1000 cells with 120 bits per cell at a 50kbps download rate weekly.				

Breadcrumbing

Figure 6 illustrates the breadcrumbing use case. An asset location is estimated periodically, and a log of these estimates are periodically analyzed. For example, an asset location might be estimated every 15 minutes, and once a week the asset breadcrumbs are processed. This technology is used for a variety of applications. For example, a shipping company may require the monitoring of tens of thousands of pallets containing valuable shipments to customers at any given time. A small, low cost, power efficient tracker is attached to each pallet adding location intelligence to the system. A long battery life for such an application is highly desired, simplifying deployment and lowering operating costs.

Breadcrumbing can be used for contact tracing in managing an epidemic. Public health agencies in affected regions can provide small, low cost, power efficient trackers to residence. If a breakout occurs at a particular market at a particular time, all residence who visited the market can be notified and treated accordingly. Residence who are not impacted can maintain normal daily routine.

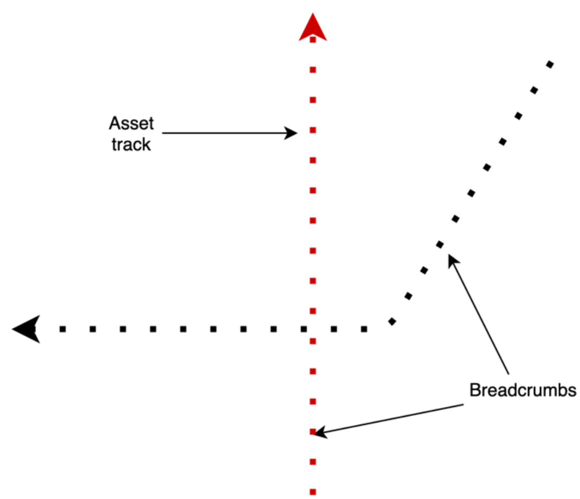

Figure 6: Geofencing application.

The battery life analysis performed above for the geofencing application is now applied to this application of breadcrumbing. See Table 3. Here, the position estimate is performed less frequently, every 15 minutes. The GPS device battery is extended to 43.9 days, and the cloud-based cellular device has a battery life of 58.4 days. The hellaPHY® devices has a battery life of 2935.4 days: 70x longer than the GPS device.

Table 3: Battery life analysis for a breadcrumbing use case.

Breadcrumbing with location logging every 15min, log reporting once per week.				
Position update rate (min)	15			
Battery capacity (mAh)	2350			
Breadcrumb weekly log size (bits)	43008			
Device A: A-GPS for location, LTE-M for data				
	PSM (Note 1)	A-GPS with LPP/SUPL in RRC Connected (Note 2)	Report location in RRC Connected (Note 3)	
Duration (s)	85440	10	2	
Average current (mA)	0.010	200.000	150.000	
Times per day	1	96	0.143	
Total time per day (s)	85440	960	0.286	
Percent of total	98.89%	1.11%	0.00%	
Total mAh used per day	0.237	53.333	0.012	
Percent of total	0.44%	99.53%	0.02%	
Total mAh used per day	53.583			
Battery life (days)	43.9			
Device B: Cloud cellular for location, LTE-M for data				
	PSM (Note 1)	Cloud-based in RRC Connected (Note 4)		
Duration (s)	85440	10		
Average current (mA)	0.010	150.000		
Times per day	1	96		
Total time per day (s)	85440	960		
Percent of total	98.89%	1.11%		
Total mAh used per day	0.237	40.000		
Percent of total	0.59%	99.41%		
Total mAh used per day	40.237			
Battery life (days)	58.4			
Device C: hellaPHY® cellular for location, LTE-M for data				
	PSM (Note 1)	hellaPHY® in low power mode (Note 5)	Report location in RRC Connected (Note 3)	hellaPHY® micro-BSA update in RRC Connected (Note 6)

Duration (s)	85919	5	2	2.4
Average current (mA)	0.010	3.375	150.000	150.000
Times per day	1	96	0.143	1.000
Total time per day (s)	85919	480	0.286	2.400
Percent of total	99.44%	0.56%	0.00%	0.00%
Total mAh used per day	0.239	0.450	0.012	0.100
Percent of total	29.81%	56.21%	1.49%	12.49%
Total mAh used per day	0.801			
Battery life (days)	2935.4			
Note 1: Assuming a nominal 10uA for PSM [1].				
Note 2: Assisted GPS with LPP/SUPL in RRC Connected assumes 150mA for LTE modem [4] and 50mA for GPS receiver [5].				
Note 3: For UE-based location it is assumed 2s of RRC Connected mode at 150mA [4] to upload location estimate.				
Note 4: For UE-assisted location it is assumed the device reports measurements to cloud server with 10s of RRC Connected mode at 150mA [4].				
Note 5: hellaPHY® in low power mode assumes a power consumption similar to RRC Idle DRX of 2mA [4] plus 6MHz 1.2v Cortex M4 at 50uW/MHz [6] plus 50% margin.				
Note 6: hellaPHY® micro-BSA update assumes almanac information of 1000 cells with 120 bits per cell at a 50kbps download rate daily.				

Abbreviations

For the purposes of the present document, the following abbreviations apply.

3GPP	3rd generation partnership project
BSA	Base station almanac
eDRX	Extended discontinuous reception
E-SMLC	Evolved serving mobile location center
GPS	Global positioning system
GNSS	Global navigation satellite system
IoT	Internet of things
LOS	Line-of-sight
LoT	Location of things
LPP	LTE positioning protocol
LPWA	Low power wide area
LTE	Long term evolution
MCU	Microcontroller unit
MNO	Mobile network operator
NLOS	Non-line-of-sight
OTDOA	Observe time difference of arrival
OTT	Over the top
PRS	Positioning reference signal
PSM	Power save mode
RF	Radio frequency
RSTD	Reference signal time difference
SLP	SUPL location platform
SUPL	Secure user-plane location architecture
TDOA	Time difference of arrival
UE	User equipment

References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

[1]	3GPP TS 36.355: “LTE Positioning Protocol (LPP)”
[2]	OMA SUPL: “Secure User Plane Location Architecture,” 2012
[3]	RP-170662: “Motivation for Higher Layers Positioning Enhancement for IoT”, Sequans Communications, 3GPP TSG RAN Meeting #75, Dubrovnik, Croatia, March 2017
[4]	Quectel BG96 data sheet, https://www.quectel.com/UploadFile/Product/Quectel_BG96_LTE_Specification_V1.0.pdf
[5]	u-blox NEO-6 data sheet, https://www.u-blox.com/sites/default/files/products/documents/NEO-6_DataSheet_%28GPS.G6-HW-09005%29.pdf
[6]	ARM Cortex-M4 data sheet, https://developer.arm.com/ip-products/processors/cortex-m/cortex-m4