Introduction
The BBC’s aim to cover every mile of the Olympic Torch relay presented a significant engineering challenge for the team involved. The Torch was carried by 8,000 bearers across the UK and Ireland. The vast majority were community volunteers participating in their local area, occasionally alongside celebrity guests. For the towns and people chosen along the 8,000-mile route, it was a once in a lifetime moment of huge importance. The BBC has a strong commitment to local broadcasting and felt it was worth attempting to cover as much of the route as possible for its audience. A dedicated website provided an interactive map (pinpointing the location of the torch at any given time), continuous picture feed (current bearer in camera) and live text feed with news and social media updates.

This document explains some of the engineering strategies employed to deliver the pictures back to Television Centre.

Covering a moving event
The Tour de France broadcasts live to many countries around the world, every year. Could the Olympic Torch Relay broadcasts deploy a similar set-up? Although similar in some respects, they are quite different events. The Tour runs for about five to six hours a day for 20 days; the Torch Relay for roughly 12 hours a day for 70 days. The Tour de France is covered with tried and tested broadcasting equipment, satellite trucks and radio camera links. To cope with the moving element, a helicopter or aeroplane is used to relay the pictures from camera bikes to a fixed satellite truck. This provides broadcast quality live coverage of the event for a TV audience. The cost of this logistically heavy set up is commercially justified because the audience is large and global. Whereas on the Torch Relay, even if there were enough satellite trucks, radio links and helicopters available to leap frog across the country for 70 days, the cost would be prohibitive.
In 2010, the team on board the Winter Olympics Torch Relay Media vehicle in Canada had the idea, early in the relay, to stream pictures of the Torch Bearer over the 3G mobile networks. It was a single camera set up with an existing 3G bonding device and was a big success with their audience.

The idea for the 2012 Torch Relay in the UK was to build on that success and aim to stream a four-camera mix for a much higher proportion of the relay than was achieved in Canada. 3G bonding was a cost effective way of covering (almost) every mile by providing a constant video feed on the BBC website.

3G bonding

Combining the bandwidth of multiple mobile data connections was becoming a mature technology by the end of 2011. There were over a dozen devices aimed at the broadcasting industry on the market. For the purposes of this document most of the devices can be considered as having two main parts; a video coder and a 3G bonding component. The video coder takes in the full quality picture from the camera and applies coding algorithms to reduce the amount of data without drastically affecting the picture.

The bonding computer at the mobile end assesses the quality of the connections available to it and sends the coded data stream across them accordingly. A server at the other end receives the data from the various streams then recombines and plays out the video. The clever part is that the video bit rate that the coder works at is dynamically changed depending on the available bandwidth. So in areas of poorer data throughput the device can still work by automatically reducing the quality of the picture being sent. In areas of good 3G connections video bit rates in excess of 4Mbit/s are achievable.

There are however some fundamental problems with 3G bonding. The bandwidth is not guaranteed, something that a broadcaster normally would steer well clear of. In some areas there simply isn’t any mobile data bandwidth available, network data coverage in the UK is not 100%. When there are mobile data connections available they are contended with other users. So the quality of the pictures broadcast depends entirely on what other people in the area are doing on their mobile phones.

The London Organising Committee for the Olympic Games (LOCOG) put great effort into encouraging as many people to line the streets to cheer on the Torch as they could. In effect the Torch would generate its own surrounding bubble of contention on the mobile data networks! All this meant that the Torch would travel through a varying signal ‘terrain’. In one town there could be great connectivity, combined perhaps with it being early in the morning and raining so the crowd was small. Another time a big celebrity will be running in a small town with poor connectivity. The crowd could be sufficiently large to prevent people even making phone calls let alone send and receive data.
Existing technology

In late 2011 many of the devices on the market were tested by the BBC and whilst the results on the move were generally good it was felt that improvements could be made to better suit the challenges of the Torch Relay.

Generally the devices available were designed to be operated by a non-technical person and would prioritise low latency at the expense of picture quality. This makes sense when you consider that they were aimed at live broadcasting from the location of a news story. The cameraman wants to push the ‘go live’ button and not be concerned with all the settings behind that. The delay on the pictures has to be small to facilitate a conversation between the reporter on location and the studio.

The other feature of this sort of operation is that the bandwidth available is unlikely to change very much. A cameraman on foot can move around a bit but more than a few hundred metres would be impractical so the bandwidth available from the networks shouldn’t change much. The contention with other users could change but most live broadcasts are a few minutes long and a bandwidth reduction due to contention is unlikely to be critical to the broadcast in that time. Many devices had other modes that would prioritise high picture quality (at the expense of latency), or would allow for storing and forwarding recorded pictures in full quality.

To get a feel for how the existing products would perform a test drive was conducted in Cornwall roughly simulating the route on day 1 of the relay. The received pictures were recorded and later examined to discover what percentage of the time pictures were present. It was observed that most of the picture break up lasted less than 30 seconds.

Regardless of what mode is used, the 3G bonding devices generally use UDP (User Datagram Protocol). Unlike TCP (Transfer Control Protocol) as used by websites and email, UDP is essentially send and forget; there is no guarantee that the data will make it successfully to the other end. Not having the data packets burdened down with the extra information TCP needs to guarantee delivery makes UDP fast enough to stream video but makes the pictures liable to break up if the packet loss gets too high. Wireless mobile data suffers from more packet loss than a wired service like home broadband. This coupled with the adaptive bit rate video coder means the picture quality follows the signal terrain. When the aggregated bandwidth available is high the picture quality is very good, when the bandwidth reduces below a certain threshold the pictures break up (see figure 1).

Modifications

After initial testing it became clear that the pictures were most watchable when they were continuous. Picture break up of more than a few seconds would quickly cause users on the website to browse elsewhere. Having high quality pictures was not a priority because they were to be

Figure 1: Comparison of streamed video and buffered video
displayed in a small frame on a website, and having low latency was also not important as no conversations were taking place over the link. So the idea was to re-write the rules of the 3G bonding device and trade low latency and high picture quality for continuousness of pictures in a constantly changing signal terrain.

In practice this meant two things:

1. Implementing a buffer to deliberately delay the pictures
2. Having the ability to set a maximum and minimum video bit rate

The buffer allows the system time to average out the peaks and troughs of the changing bandwidth (see figure 1). Setting a maximum video bit rate allows the system to catch up when coming back into an area of high data throughput. The minimum data rate is simply to provide a cut off below which the pictures are of such poor quality they are deemed as not worth having.

Testing

Mobile Viewpoint, a Dutch company, whose 3G bonding product is the WMT (Wireless Multiplex Terminal), took on the challenge of modifying their software for the Torch Relay. Their approach was to split the incoming video stream into 15 second .mov files and define the buffer in 15 second chunks. The user could set the desired length of the buffer and the maximum and minimum video bit rate.

As each file was created at the mobile end it would be transferred to the server (see figure 2). The extra time introduced by the buffer allowed Mobile Viewpoint to adjust the settings of the UDP protocol used by the WMT to allow a much higher latency for the data transfer. This made it more efficient and better suited to wireless data links.

When the number of files at the server matched the requested buffer length it would start playing out the video. If a file could not be sent immediately it would be put in a queue at the mobile end and sent when the signal improved. As soon as more than one file was in the queue at the mobile end the video bit rate would be reduced so subsequent files were smaller and therefore could be sent much quicker. The server would continue playing the video in its buffer until the buffer ran out. At the mobile end the queue would build until it reached the length of the buffer and then the oldest clips would be discarded.

This new mode gave the engineers on board the Media Vehicle the flexibility to fine tune the settings through testing and if necessary during the relay itself. The settings most of the relay was run at were a buffer length of 2 minutes (so 8 x 15 second video files), a maximum video

Figure 2: Buffered approach of Continuous Picture Technology
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bit rate of 1500kbit/s and a minimum video bit rate of 400kbit/s. In average conditions it would take 7 to 10 seconds to transfer a 15-second video clip. When it took longer than 15 seconds to transfer a clip the queue would build and the size of subsequent clips would fall to make them faster to send.

The test that was conceived to prove the effectiveness of the modified software was to rig the equipment on a trolley and wheel it around Television Centre, a task that attracted puzzled looks and many questions! A standard route was settled on that started on the fifth floor and used various lifts and the basement of the building to simulate a signal terrain that varied from very good data throughput to a complete blockage.

The software was fine tuned in this manner and the settings mentioned above were arrived at. The system was then road tested for three days around Cornwall and Wales and found to be very effective at maintaining as continuous a picture as possible. This additional mode was called CPT (Continuous Picture Technology) and is now a standard mode on Mobile Viewpoint’s WMT product.

Guaranteeing the stream

The CPT mode did a good job of optimising the process of sending a stream of pictures over the 3G networks for a long period of time but it couldn’t work miracles. If the data throughput wasn’t good enough for a while then the frame on the website went black and the audience would rely on the live text feed for information about what was going on with the Torch.

LOCOG aimed to make each day contain several moments of significance in various ways. It could be that the runner was of great interest or the place the Torch was being carried through was nationally recognisable. As previously discussed it was close to impossible to predict accurately whether 3G bandwidth would be present or not. Having a team going ahead of the torch surveying the 3G bandwidth might have pinned down one element, but with no way to know how many people are going to turn up to watch and what those people will be doing on their mobile phones, it would have been pointless. So there needed to be a way to guarantee the pictures when it was considered editorially justified.

Occasionally the team used tried and tested broadcasting tools, namely radio camera links and satellite uplink trucks. There were a couple of issues with doing it this way. Firstly it meant that a switch had to take place at Television Centre to change the web feed from the pictures coming into the WMT server to the pictures coming in from the satellite truck. Secondly with the 3G pictures being deliberately delayed and the satellite pictures being live there would be an odd time discrepancy. The switch needed to be timed carefully and had to be called for by the editorial team and implemented by the technical team. It couldn’t be justified to have dedicated a team just for this function so it meant switching tasks at different moments in the day. All this led to an over complicated process for those involved.

The Torch technical team solved this by taking advantage of the increasing prevalence of Internet Protocol (IP) systems in broadcasting. In recent years the BBC has built a number of lightweight satellite trucks that use an IP video coder, these are generally known as VSATs (Very Small Aperture Terminal). Two of these transmission vehicles were built to cope with the extra coverage the Torch and Olympics would require. Amongst other things they were capable, in the BBC set up, of providing raw internet at a data rate of up to about 3.5Mbit/s.

Most 3G bonding devices allow the user to add to the 3G internet connections with a Wi-Fi connection and an Ethernet connection. For the live cameraman broadcasting from a town square this can help enormously as they can use Wi-Fi from a local café or pub to improve the quality of their broadcast. With the torch constantly moving Wi-Fi was of little use; by the time the credentials had been obtained and entered the Media Vehicle would have passed out of range.
So the VSATs provided the ability to put uncontended raw internet anywhere on the route and the WMT could take and use that raw internet. The question was how to connect a constantly moving vehicle with one that had to remain static?

**Cobham NetNodes**

Cobham Broadcast offered a solution that had been developed and used in the Surveillance industry and had recently been packaged into a broadcast version. Their NetNode product is a nodal system of IP radio links that create a self-forming and self-healing mesh. In practice it could work like a very long stretchy cat 5 cable! When several nodes are meshed together the IP traffic going into one of the nodes will be available at all the other nodes in the mesh. Having nodes allowed their coverage to shaped around the Torch route and therefore offered much better range than a point-to-point system.

5 nodes were purchased for the Torch Relay, in the 5GHz band, with a system bandwidth of 5MHz. They can transmit at up to 30dBm using COFDM (Coded Orthogonal Frequency Division Multiplexing). In terms of data throughput the more nodes in the mesh the less data throughput is possible as the data has to be shared more ways. The other way the data throughput can be affected is by the mesh's ability to change the parameters that it works at in order to keep as many nodes in the mesh as possible. So if a node is moving away from the rest of the mesh the modulation and Forward Error Correction will be automatically changed to make that link more robust and of greater range to keep that node in the mesh. All the links in the mesh will change to these settings as well and this will reduce the data rate that can be sent through the mesh.

One node was installed on the media vehicle and connected to the Ethernet port on the WMT; it would be one end of the mesh where data would be put in. One or other of the nodes installed on each of the VSAT vehicles would be the other end of the chain. In the middle of the mesh were the node on the BBC News helicopter and an ad-hoc node to be rigged in an advantageous ground-based position locally (see figure 3).

The first challenge to overcome with this set up was getting the WMT to accept this connection. The WMT assesses and prioritises the connections available to it (3G, WiFi or Ethernet) based on latency (ping times) and packet loss. Despite the originating bandwidth being reliable, with COFDM links and a satellite uplink in the chain the WMT rated the connection as poor and was reluctant to send data that way. Mobile Viewpoint tweaked their software once again to recognise a satellite connection on the Ethernet port and trust it more than it otherwise would trust a high latency connection.

The other challenge involved was logistical. The editorial decision to deploy the VSATs in this way would be made, at the earliest, the day before but usually on the day. The team in the VSATs would drive to the location of the runner to be ‘guaranteed’ and aim to set up a mesh to cover as much of the route as possible in the time available.

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**Figure 3: Using NetNodes and a VSAT to provide the WMT with guaranteed IP bandwidth**
This involved finding useful parking for at least one of the VSATs in a location where it could see the satellite in the southern sky but also be close to the route.

The huge advantage to guaranteeing the pictures this way was that all the effort needed was on location and it required no manpower further down the signal chain at TV Centre or beyond. The pictures would seamlessly come out of the WMT server at TV Centre and be routed on accordingly. No switching needed to take place at any point as the decision on which data route to use was made automatically by the WMT on the Media vehicle. This method was used on dozens of occasions throughout the Torch Relay. Whilst it wasn’t possible to categorically determine after each usage whether or not the VSATs and NetNodes’ contribution made the critical difference between the pictures being there or not it was possible to chart the traffic going through the VSAT. With the graphs generated it’s possible to see the files being sent in 15 second windows and the data throughput increase due to the WMT finding that connection to be better than the local 3G (see figure 4).

**The future**

Broadcasting the Olympic Torch was a unique engineering challenge. Whilst a Torch Relay is staged every couple of years, the country is different, the route is different and often the format of the event is different. Two years is a long time in broadcasting technology and changes in that area will continue to affect what is possible. The advent of a 4G (LTE) network in many of the major cities in the UK since the 2012 Torch Relay would certainly change what would be possible if the Torch was run again in 2013. Based on past form the Olympic Torch won’t return to the UK until 2076, but there’s always the Glasgow 2014 Queen’s Baton Relay to look forward to!

**Figure 4: Graph showing VSAT traffic sent by the WMT over the NetNodes**