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Virtualized Sub-GHz Transmission Paired with Mobile Access for the Tactile Internet

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Abstract—**The Tactile Internet has highly challenging technical requirements. For example, the end-to-end latency for the sensation of touch to be realistically conveyed to the end-user via communications, for the purpose of that end-user implementing control actions in response to that touch, must be less than 1 ms. This is equivalent to only 300 km propagation at the speed of light. Such constraints mean that many of the conventional approaches to communications, e.g., higher-layer retransmissions for reliability and congestion control, and even link-level retransmissions for reliability, can not apply. In this paper, we propose a novel solution for combining licensed access for reliability and control, with virtualized low-frequency sub-GHz access for good coverage and low latency, also removing receive-acknowledgement based reliability and congestion control mechanisms. Through the removal of these reliability/retransmission mechanisms, and by achieving a more direct path to the receivers through virtualization and better coverage maximizing (wireless) routing options, or even transmitting directly, this proposed solution minimizes latency and jitter while still being able to achieve the extremely challenging requirement for reliability of the Tactile Internet. We argue the benefits of our solution with reference to a major trial within the Ofcom TV White Spaces Pilot in the UK, as one readily-available means for such sub-GHz transmission. We also provide the example of such a realization as a viable means of achieving remote surgical operations across the London, UK area, with the surgeon(s) being physically located in only one or a small number of London hospitals.**

Keywords—tactile/haptic communications, 5G, virtualization, applications

I. INTRODUCTION

The Tactile Internet represents perhaps the most challenging application for mobile and wireless communications, and a prime example of a target application for the pioneering capabilities being proposed for 5G

communications systems [1]. Two of these most-challenging aspects include a latency of less than 1 ms, and "five-nines" reliability—a one-in-a-million chance of failure [2], [3]. These are respectively necessary such that the sensation of touch leading to control movements from the user can be realistically conveyed (noting also that audio-visual aspects, e.g., video of the other end of the link at which the sensation of touch applies, must also be carefully synchronized with this), and safety- or mission-critical applications can be achieved. One prime example of the use of the Tactile Internet under such challenging constraints is for remote medical operations [4], such that the surgeon—performing the operation at a distant location from the patient—can feel the sensation of touch and force-feedback through haptic clothing and other equipment, and can implement control actions and adjustments in response.

Although there are circumstances and assumptions (even in the aforementioned world of medical applications) in which such a low latency can be relaxed somewhat, achieving a latency of less than 1 ms is of course challenging—noting that light can propagate only 300 km in this duration. Thus, in order to achieve such latency, it is necessary to remove all the time-consuming signalling that is taken up for reasons such as data transfer error or loss detection and correction, and congestion control, among others. Moreover, it is necessary to keep the communication over the most direct possible physical path. The use of low-frequency sub-GHz spectrum for such communication, increasing wireless coverage, combined with the use of virtualization facilitating network nodes being set up almost anywhere where there is a computer and a form of basic standardized radio capability, can achieve the transmission over such a more direct physical path—multi-hop (for a small number of hops) if necessary. Such necessary capabilities of course go in tandem with a range of other solutions, including minimizing communication frame sizes (strongly linked to the development of appropriate tactile/haptic codecs and link coding, among other aspects), and the use of artificial intelligence to assist the Tactile Internet, among others.

This paper proposes combining virtualized sub-GHz radio transmission for low latency, with licensed access for reliability and control, to achieve the Tactile Internet.
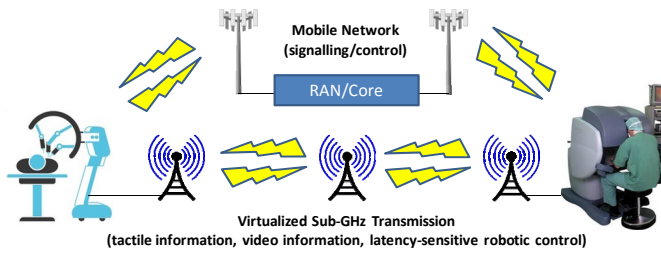
Fig. 1. The combined use of virtualized Sub-GHz transmission with licensed access (mobile network example) for the Tactile Internet. Remote surgical operation example.

Section II of this paper introduces the proposed idea. Section III studies the performance the approach through a trial within the UK's Ofcom TV White Spaces Pilot—noting that TV White Space (TVWS) is one prime example of a medium that could readily realize such sub-GHz spectrum. This section also links such performance assessment to an example of the Tactile Internet being used for remote hospital surgery in the London, UK area. Finally, Section IV concludes this paper.

II. PROPOSED TACTILE INTERNET SOLUTION

Our proposal, illustrated in Figure 1, combines the rapid transfer and excellent coverage but unreliable sub-GHz transmission, with highly reliable mobile access using licensed spectrum. The sub-GHz transmission is unreliable as a baseline assumption, as it is implemented unidirectionally and uncoupled in each direction, thereby not giving the option of implementing acknowledgements or negative acknowledgements to trigger retransmissions. This rapid transfer sub-GHz transmission can be adapted to the situation in terms of quality of channel, or ruled out if access is not possible to achieve with the degree of reliability that will be necessary for the Tactile Internet, through coding. Adaptation is achieved using feedback/control provided over the reliable access of a paired mobile network. Moreover, other critical information linked to the Tactile Internet session might also be carried over the mobile network, such as instructions to/from the surgeon to local human assistance at the point of the operation.

Importantly, the sub-GHz transmissions under our proposal are achieved by virtualization, such that computational capability with basic, standardized radio processing and front ends can be opportunistically used as and where needed in order to minimize the multi-hop propagation path. In an envisioned fully virtualized core and wireless access network, the different network functions (such as, for example, mobility management, deep packet inspection, firewalls, etc.) could be virtualized under the Network Function Virtualization (NFV) framework. Within ETSI, the NFV framework has been defined with the central aim of providing the means for a flexible and dynamic composition of network functions to create a plethora of different services. Available spectrum including the abovementioned sub-GHz frequencies could be included within a so-called spectrum network function that can be allocated on demand in addition to other virtualized network functions (vNFs), to create a service through vNF chaining. In that respect, spectrum slicing could be managed by the so-called VNF Management and Orchestration (MANO) architecture as defined within ETSI. The MANO, which will be overlooking the actual physical resources from the substrate network, will be responsible for, inter alia, creating a service chaining that provides also delay bounds for highly delay sensitive applications as those discussed in the sequel. Details of how spectrum resources could be integrated to compose a vNF within the MANO overall architecture are beyond the scope of this paper although are being investigated in EU 5G-related research projects.

The Tactile Internet example presented in Figure 1 is that of a surgeon doing a remote operation on a patient. Here, the highly time-critical tactile/haptic information, along with video information which incidentally must be highly synchronized with the tactile information, is conveyed from the patient being operated on (on the left side of Figure 1) to the surgeon performing the operation (on the right side of Figure 1). Time-critical control information from the surgeon's inputs to the remote robot performing the operation is sent in the other direction. There are no retransmissions on the sub-GHz link, given that by the time that such retransmissions would be sent the information would be of greatly reduced or no use, and it would generally not be possible to buffer due to latency requirements. Moreover, the size of "frames" for the transmission is kept to a minimum.

Given the nature of the sub-GHz transmission and the types of scenarios in which this system is likely to be deployed, fading of the signal will vary slowly. Given this, the mobile system will be sufficient to convey information on changes in signal quality, such that adjustments can be made to coding in order to address variations in channel quality adequately fast enough. Moreover, in cases where multiple channels/frequencies might be used, the mobile system might also carry information on the quality (e.g., interference levels)
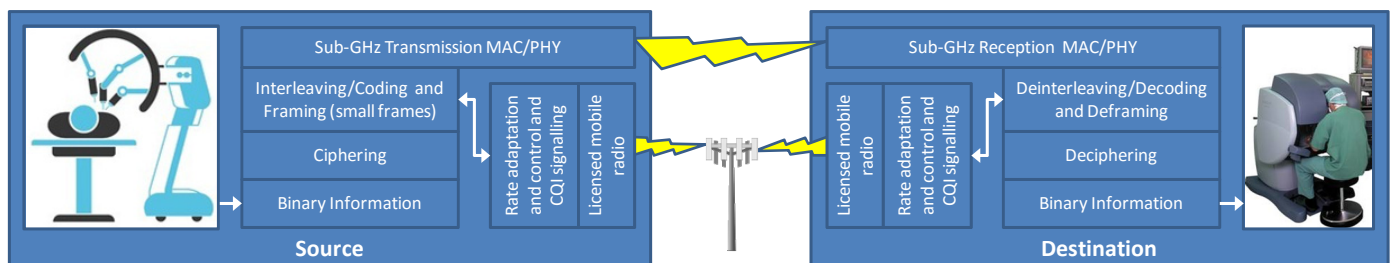

Fig. 2. Simplified block diagram of the source and destination under the scheme.
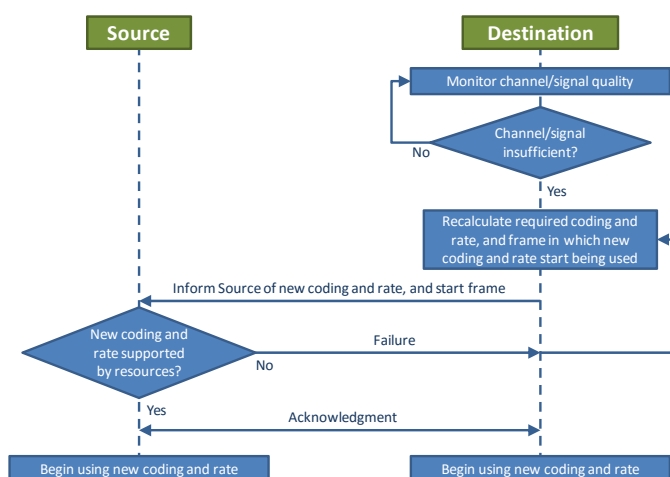
Fig. 3. Signalling and flow chart for source/destination coding and rate change decisions.

in alternative channels or frequency options, as sensed by the sub-GHz radios at the other end of the link.

Given such observations, Figure 2 depicts an example of the protocol stack for the concept – both the sub-GHz transmission and the mobile transception essentially acting as a control bearer for the sub-GHz transmission. The core essential blocks in this figure are explained as follows.

A. Ciphering, and Security in General

Security is absolutely essential in most Tactile Internet scenarios, including for the control information that a Tactile Internet user might convey in the opposite direction. For instance, if someone were to hack the connection through some form of man-in-the-middle attack, there would be severe consequences for the safety of the operation depicted in Figure 1. Ciphering of the information is therefore necessary on the sub-GHz communication path, noting that security will anyway be good for the licensed mobile radios. Additionally, strong authentication and general security control will be necessary—this can be dealt with through the licensed mobile connection depicted in Figure 2.

B. Small Blocks/Frames

It is of absolutely paramount importance that block/frame sizes (hence transmission durations) are kept small in Tactile Internet scenarios, such that the transmitter and receiver don't have to wait that duration in order to obtain the information to respectively build and recover the information in the frame/block.

C. Intelleaving/Coding

These must be present as in almost all digital communication systems. However, they have increased importance role in the context of our proposal for the Tactile Internet, in that adaptation of them is by intention the only means of providing reliability for the sub-GHz transmission. Control of the interleaving/coding, as well as other aspects of the Tactile Internet session in general, are achieved through the mobile network.

D. Control Through Licensed Mobile

The licensed mobile is necessary to underpin the whole Tactile Internet session. In theory, this underpinning could alternatively be achieved by any form of reliable Internet access, such as an Ethernet connection providing Internet access at each end of the link. However, we present the use of licensed mobile radio here as applicable in the most number of scenarios without implying additional wired infrastructure.

In the example presented in Figure 2, and expanded on through the signalling/flow chart of Figure 3, the quality of signal/channel will be monitored at the destination. This monitoring allows direct derivation of the coding and the raw uncoded transmission rate (e.g., modulation) required for transmissions from the other end of the link in order to achieve the required level of reliability, while still maintaining the required decoded data rate for the tactile information and paired audio/video, among other information that the Tactile Internet session might be carrying. A decision on changing the coding/rate, if necessary, will therefore be made at the destination. That decision as well as the timing of the change (i.e., the frame/block in which the change will be made) will be conveyed to the source via the licensed mobile radio, and the source will check whether it is available to support the change, e.g., whether it has sufficient remaining computational resources to implement the change. If the source has sufficient resources, the decision will be acknowledged among the source/destination and the change will be made starting from the indicated frame/block; if not, the source will inform the destination and the Tactile Internet session.

If at any instance it becomes apparent that the quality of the connection is becoming insufficient, e.g., due to temporary fading or another issue, and the change in coding cannot be made in sufficient time (e.g., due to intermittent connectivity of the mobile radio, or the fading having varied too quickly), then the control of the operation (remote robot) via the connection will immediately freeze in the current state, and the surgeon will be immediately alerted. Likewise, the same will happen if the sub-GHz connection is disrupted, e.g., due to unexpected shadowing. The operation will continue once the assurity of Tactile Internet session is regained. It is expected that the quality of the deployment, particularly for the safety-/mission-critical case of such a medial operation being performed over a Tactile Internet session, will be such that the chance of such failure is extremely low.

It is further noted that the control provided by the licensed mobile radio can be used also for other means, e.g., for the surgeon to pass digital instructions to people in the operating theatre, and for other aspects of the operation to be dynamically/optimally configured (e.g., the required characteristics/performance of the audio/video).

III. EVALUATION OF THE CONCEPT AND IMPLEMENTATION IN TV WHITE SPACE

King's College London has led a major consortium participating as a trial within the Ofcom TV White Spaces Pilot, a pioneering regulatory-driven test of TVWS technologies in the UK, based on the UK/EU database-based framework for TVWS [5]. The purpose of this trial has been to
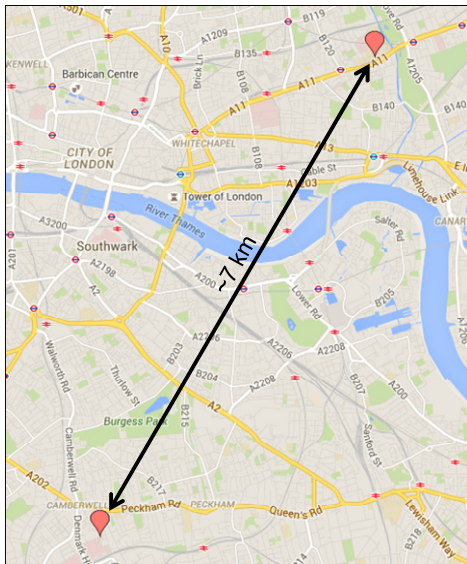
(a)
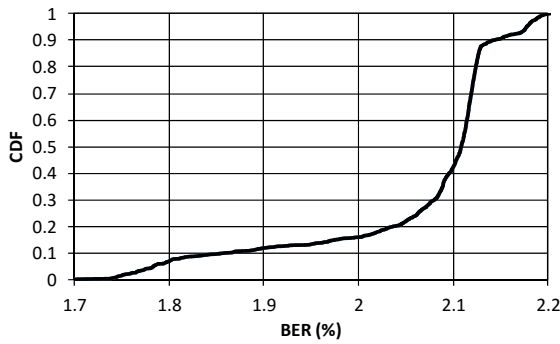
(b)

Fig. 4. (a) The assessed long-distance link between King's College London Denmark Hill and Queen Mary University of London Mile End, and (b) the observed BER distribution over that link using Carlson Wireless RuralConnect radios, in a configuration able to achieve up to ~1 Mbps throughput.

demonstrate the viability and performance of TVWS and the underlying supporting framework, before the framework and TVWS technologies are brought to the commercial/market stage. Our trial has yielded a number of significant observations and assessments of the potential for TVWS, among other aspects, e.g., yielding results on the availability of TVWS across the UK, the capacity that can be achieved using TVWS, link performances in TVWS, radio designs supporting aggregation in TVWS, and other aspects [6].

It is noted that TVWS is a prime example of a sub-GHz medium that could be readily used for the proposal provided in this paper. Moreover, such is the nature of TVWS frameworks in the UK/EU, USA and elsewhere, that Internet access has to be provided to white space devices such that they can access a geolocation database in order to obtain information on permitted TV channel usages and EIRPs, based on their locations and technical characteristics. Otherwise, the white space devices are not allowed to transmit. Indirect and even multi-hop communication with the database through a master-slave hierarchy is supported, however, in the vast majority of cases it will be strongly preferable for the radios to

be directly connected to the Internet to access the geolocation database as master devices. This is made possible for the white space radios at both ends of the link through the licensed mobile radio access under our proposal in this paper.

Through the participation in the Ofcom TV White Spaces Pilot, we present our results based on real, actual TVWS performance within the UK framework—noting that the same framework has been brought to the ETSI EN 301 598 harmonized European standard, so therefore applies to TVWS usage across the EU for any countries in which the concept of TVWS is taken up.

A first example we assess here is the case of a very challenging 7 km line-of-sight TVWS link between King's College London Denmark Hill Campus, and Queen Mary University of London Mile End campus. This link, which is pushing towards the most challenging that can be supported within the UK under the Ofcom Framework, is depicted in Figure 4(a). It is noted that both ends of the link are at locations of major hospitals or medical schools within London, hence, it would be possible for a skilled surgeon to remotely sit at one end of the link to perform an operation at the other end of the link. For example, a surgeon could be located in the medical school at Queen Mary University of London, and be performing the operation remotely at King's College Hospital in Denmark Hill, which is closely associated with King's College London Denmark Hill campus.

Figure 4(b) shows what can be achieved with Carlson Wireless RuralConnect white space radios over this link in terms of BER distribution, for a configuration which should be able to achieve a data rate of up to ~1 Mbps. It is noted that, for such a configuration, the BER distribution remains relatively stable. Further, through coding applied to this case, it would be possible to realize the required low error and high reliability for Tactile Internet scenarios. We note here that the Carlson devices are a good representation of what is generally achievable in TVWS, noting also that such links in the UK experience an extremely high level of receive interference, eroding their performance. Nevertheless, we have investigated shorter line-of-sight distances of 5 km, and our investigation has indicated that SINRs of comfortably more than 15 dB should be achievable in areas comparable to London at such frequencies, with a transmission EIRP of 36 dBm (the maximum ceiling according to the Ofcom/ETSI TVWS framework), Hata path loss modelling, an appropriate antenna gain of 15 dB, noise of -105 dBm (i.e., that the receiver is listening to the entire 8 MHz TV channel), and even using an extremely poor receiver noise figure of 10 dB. This indicates the viability of such distances.

Figure 5 gives the locations across a large area of England in which it is possible to aggregate a significant three-channels or more of available TVWS, for a high allowed transmission power of at least 30 dBm EIRP and a transmitter antenna height of 30 m. This Figure was obtained using the logical control aspects of a white space device, created at King's College London, to methodically query a real white space database for locations at a resolution of 0.01 degrees in both Latitude and Longitude. Figure 6 presents a zoomed-in view of the contiguous or non-contiguous case for the London area,
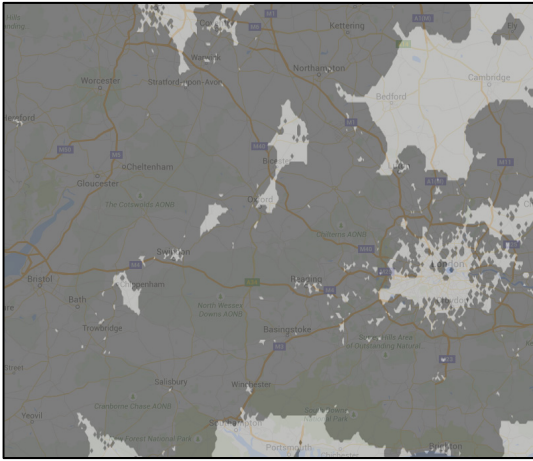
(a)
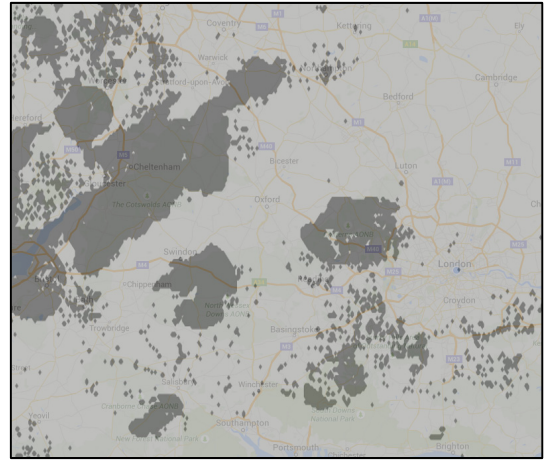
(b)

Fig. 5. Availability of three or more channels with at least 30 dBm Tx EIRP for a wide area of England, ETSI Class 3 white space device, 30m white space device height (darker areas indicate no availability): (a) contiguous-only channels, (b) contiguous or non-contiguous channels.
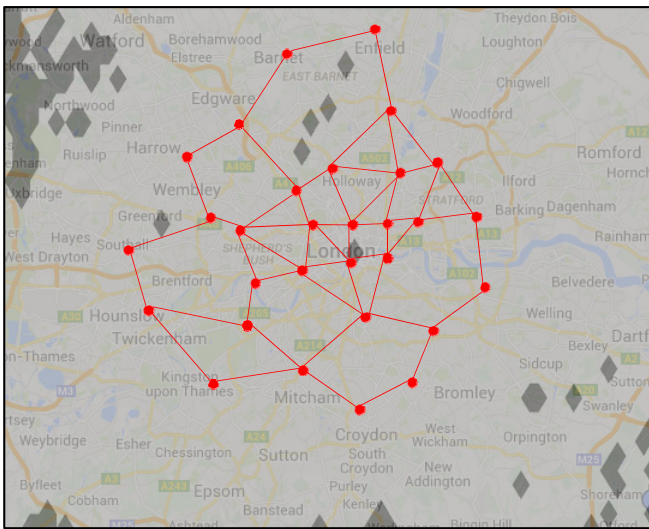

Fig. 6. Availability of three or more channels with at least 30 dBm Tx EIRP for the London area, ETSI Class 3 white space device, 30m white space device height (darker areas indicate no availability). Locations of a small proportion of the major hospitals, and possible TVWS links between those hospitals limited to less than ~5 km, are also depicted.

where in this example, the locations of a small proportion of the major hospitals are superimposed, as well as possible TVWS links between those locations. These links are limited to 5 km, the distance that we ascertain as being achievable with a good SINR as discussed above. It is abundantly clear from these results that very significant TVWS availability can be achieved for bandwidths comparable to a 20 MHz LTE carrier. However, the case for contiguous aggregation (Figure 5(a)) is challenging across much of the considered area of England, despite having some areas of good availability—much of the London area being a prominent example. It is also clear that, for the London area presented, it is possible to create a network among hospitals using TVWS for such a purpose. Using these possible multi-hop TVWS links, it is clear that in the vast majority of cases a surgeon could sit in

one hospital (e.g., a central one such as St. Thomas') to perform an operation remotely in almost any other, with the network path between the hospitals being close to line-of-sight. Hence, as long as basic standardized virtualization capabilities existed in these hospitals, with standardized radio aspects, e.g., on the roof, it would be possible to invoke the hops on these links and perform the operation remotely.

IV. CONCLUSIONS

This paper has proposed the combined use of virtualized sub-GHz radios and licensed mobile radio to realize the Tactile Internet with required delay bounds. It has argued the concept through the example of the Tactile Internet to achieve remote medical surgery. It has shown, using results obtained through a major trial within the Ofcom TV White Spaces Pilot, that such a concept is feasible using TV white space as the sub-GHz medium.

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