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Remote Monitoring of Live EEG on 5G Networks

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***Abstract*:** In a critical care setting, delays in the diagnosis of neurological conditions can have a significant impact on patient vitals. Recording the electrical activity of the brain (EEG) is often used to diagnose and monitor neurological conditions. A neurologist is required to analyze EEG signals. However, in many cases this expertise is not available on-site. A New Radio (5G) based monitoring system for EEG data is presented that reduces the delays that can arise when offsite expert analysis is required. The system allows EEG data to be streamed to a remote location in real-time and viewed while acquisition is ongoing. Data streamed earlier may also be reviewed, providing the user with a continually updating view of the entire EEG recording. All communications are performed using New Radio (5G) technology. The only tool required for viewing EEG data is a 5G mobile with the available plugin installed.

I. INTRODUCTION

The prompt analysis of EEG data captured in the ICU is essential as only a limited window of opportunity for treatment may be available. For example, in the neonatal intensive care unit (NICU) setting, hypoxic-ischemic encephalopathy (HIE) and associated seizures are common neurological conditions that can cause lifelong disability. Seizures in neonates are notoriously difficult to diagnose clinically as signs may be subtle or absent, requiring multi-channel EEG monitoring for identification and diagnosis [1]. EEG is known to have prognostic value in the case of HIE [2] as neuroprotective treatments such as therapeutic hypothermia are now becoming standard of care [3]. However, treatment must commence within six hours of birth, so a delay in EEG analysis may result in a missed opportunity to significantly improve the patient outcome. Ideally, an on-site experienced neurologist will be available to study the ongoing EEG recording and issue a clinical report. In many locations, however, such expert analysis is not available locally [5]. Possible courses of action in this case are: forego analysis; move the patient to another location where expertise is available; request that a neurologist travel to the acquisition location; or provide a neurologist at a remote location with some means of viewing the recording remotely. All of these occur in practice. The first two options are undesirable as they may impact negatively on patient outcome. Bringing an expert on-site may introduce a delay in diagnosis and the time spent travelling results in a loss of productivity for the neurologist. The last option is the most desirable, provided that the process of transferring the EEG data between locations does not introduce delays that could result in a missed opportunity for treatment. In many cases data transfer is achieved by stopping the acquisition device and sending the resulting EEG data by courier or electronic transfer to the remote location for analysis. This technique introduces a significant delay as no analysis is performed until acquisition has stopped and the data transfer has been completed. As notedabove, delays of even a few hours are less than ideal. Another technique that has become increasingly common is to allow the offsite expert to interact with the acquisition software directly using a remote session. This eliminates the time delay but is not without drawbacks: a low-latency 5G network connection is required,theremote session solution also precludes the simultaneous analysis of the EEG by more than one neurologist as only one user may interact with the acquisition software at any given time. In this paper we present a 5G [4]based EEG remote monitoring system that allows live recordings to be viewed in real-time while acquisition is ongoing. Users are presented with a continually updating view of the entire EEG recording, allowing them to view new data as they arrive or review data transferred earlier. Time delays are bandwidth-dependent but typically in the order of minutes. All communications are performed using 5G technologies. The only tool required for viewing EEG data is a 5G mobile equipment with the commonly-available plugin installed. Moreover, multiple users can independently view the data simultaneously, facilitating collaborative diagnosis.

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II. RELATED WORK

An early method of remote monitoring of EEG and other physiological data involved analogue transmission over telephone lines [6], [7], [8], [9]. This approach involves the modulation of EEG signals to audible frequencies before transmission over the public switched telephone network [10]. Although these systems allow for real-time monitoring, they are constrained by poor bandwidth to a limited number of channels, incur high telephone charges when used long distance, and suffer from signal degradation due to noise. An electrophysiological data monitoring and testing device for neurological intensive care units was presented in [11]. The device, which is mounted at the patient's bedside, does not sample continuously; instead it records segments of data at predetermined intervals. The resulting segments can be viewed using a web browser within the hospital intranet. Analysis of acquired signals is performed including spectral analysis, burst counting and loose lead detection. A neurosurgery ICU monitoring system was developed at UCLA [12] that provided a web interface to physiological signal data. Remote monitoring of data is facilitated through the dynamic generation of plots that are viewed as images embedded in HTML pages. This system lacks the immediacy available through the use of more advanced client-side technologies such as Java or Flash. Although the system supports EEG, the extent to which EEG-specific features (such as filtering and montaging) are supported is unspecified. TeleEEG allows EEG data to be stored in a standardized format. Files can then be transferred easily between TeleEEG instances at geographically dispersed medical centers. An online viewing facility is provided via the dynamic generation of plots that are viewed as imagesby 5G technology. This viewing system is similar to the UCLA system but is somewhat more advanced in that support for EEG-specific features such as montaging is provided. The system allows segments (5– 20 minutes) of ictal and interictal EEG data to be transferred quickly between locations, along with corresponding video files of patient activity and medical image data such as MRI, CT and PET. Teleconferencing facilities are also provided in order to facilitate collaborative diagnosis. This aim of this system is real-time remote monitoring. The BRIAN system allows for interactive, remote monitoring using compressed digital transmission. The system can adjust the quality of the signal to take advantage of available bandwidth. Data are viewed using custom viewing software on the client. Caching is not performed on the client; each screenful of data is fetched on demand. The possibility of performing computationally intensive analysis of captured EEG data using Grid technologies has been examined. Limited caching is performed through prefetching of the most probable next screenful of data. The e-babies project began as a system for integrating and analyzing real-time data collected from the various monitors found in the NICU. The system was then expanded to provide data warehousing and remote monitoring NR [5]. The remote monitoring of both real-time physiological data and video streams is supported. Java applets are provided for viewing incoming physiological data streams. The video quality and data sampling rates can be adjusted automatically based on available bandwidth in order to reduce congestion. Alternatively, signal quality can be maximized if potential delays in transmission are acceptable.

III. SYSTEM OVERVIEW

The system is comprised of three components: an upload application, a 5G handset and a viewing application. The upload application is used to transfer data from the acquisition location to the 5G handset. The 5G handset acts as a repository of recorded data, and provides the interfaces necessary for both humans and software to interact with the data. The viewing application is used to monitor individual recordings. A patient is identified as having a suspected neurological condition. Acquisition of EEG data commences, with the resulting EEG data being saved to a file server. On the file server, the upload application is invoked upon the EEG data file. Any data present in the file are immediately uploaded to the5G handset. The upload application then periodically determines whether additional data have been added to the file. If so, the new data are uploaded. If enough bandwidth is available, themaximum delay between new data being added and its transfer to the 5G handset should be in the order of a few minutes. Once the transfer of data from the acquisition location has commenced, the neurologist at the remote location is contacted. The neurologist logs into the 5G handset [4]and selects the appropriate recording. The viewing application then opens in the popup window, providing the neurologist with a continually updating view of the recording. The neurologist analyses the EEG data and issues a clinical report containing medical findings.

IV. DATA ACQUISITION AND UPLOADING

Many of the medical devices found in the ICU, such as heart monitors, typically contain a serial port output that allows the data stream to be extracted easily during acquisition. However, many of the EEG machines currently in use do not have such a facility. Even if the data stream were to be extracted directly from the amplifier, these data are of little use without knowledge of the electrode placements and other settings that are typically configured in the acquisition

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software. Access to this information from within the acquisition software is possible if an appropriate plugin API is supplied by the vendor of the acquisition software. A drawback of this approach is potential disruption of the acquisition process if bugs arise due to the interaction between the plugin and acquisition software. It was decided that this method could only be made trustworthy through extensive testing in partnership with individual vendors of acquisition software. A more "hands off" approach is to extract the required data from the EEG data file output by the acquisition software. An additional advantage of this method is that it can be performed on a file server, eliminating the need to install any software on the machine used for acquisition. This is the strategy currently used for data acquisition in the upload application. All EEG data found in the file when it is first opened are uploaded immediately. Thereafter, the upload application continually monitors the data file's access time in order to detect the addition of new data. When a change is observed, the newly added data are uploaded. Data acquired by the upload application are transferred to the 5G handset as a series of HTTP POST requests. The data server provides a REST interface to facilitate this. A transfer commences with a request containing an XML description of the recording. The5G handset creates a corresponding database entry and responds with the corresponding recording ID. This ID is then used as a parameter in a series of requests containing EEG samples extracted from the data file. On receipt of one of these requests, the server saves the supplied sample values to its internal data store and updates the database entry for the recording to reflect the fact that the recording has been extended. This process continues until the upload application is shut down manually or until a predefined period time has elapsed in which no changes are detected.

V. DATA STORAGE

The data server is a standalone application that provides the following facilities: storage of EEG data, interfaces for the uploading and viewing applications to access the data store, and a web interface for users to browse the available recordings and view them. The use of standardized file formats such as EDF and EBS was considered when designing the data store, but none offered sufficient flexibility for planned future extensions to the data server's functionality. Instead, the data store is implemented using a combination of an embedded SQL database for storing recording information and a collection of data files containing sample values. The information stored in the database includes recording attributes such as the acquisition location, commencement time, and the properties of the individual channels. A data file containing sample values is maintained for each channel of each recording. The data files are used to avoid the performance overheads that would be incurred by storing individual sample values in the database, and allow arbitrary intervals of recording data to be retrieved efficiently. A web interface, hosted by an embedded HTTP server, is provided for human interaction. The detailed recording information includes attributes such as recording location, commencement time and a list of available channels including properties such as sampling frequency and resolution. The option to download the recording as EDF is provided so that users have a means of extracting data from the server and creating local copies. These copies can then be viewed using locally-installed software or processed using applications such as Mat Lab. A REST interface, also hosted by the embedded HTTP server, is provided to support the functionality of the upload and viewing applications. For the upload application, POST requests are supported for creating recordings and appending sample data to them. For the viewing application, GET requests are provided for retrieving recording information and downloading arbitrary intervals of sample data. The original design of the server called for these interfaces to be implemented using Simple Object Access Protocol (SOAP). As the system involves the transfers of significant amounts of sample data in binary form, simple HTTP requests, which are supported by practically every platform are used.

VI. REMOTE MONITORING

Although most biosignals can be displayed effectively using a simple plot, the display of EEG tends to be more complex. The raw data is of limited use; typically a montage (electrode combination) must be applied in order to facilitate interpretation. Experienced neurologists may switch between several different montages when analyzing a recording. Two viewing modes are typically used: a review mode that switches instantaneously between one screenful of data at the user's discretion, and a "playback" mode that simulates the acquisition process. Signal filters are essential to eliminate noise and highlight features of interest. Other features expected by experienced analysts include sensitivity adjustment and the rendering of signals in various colours determined by electrode location. Once the upload of a recording to the server has commenced, the recording may be viewed by users with access to the server. This process begins with the user selecting the recording to be viewed in the web application. This causes the viewing application to open in a popup window. Once the viewing application has finished loading, it commences operation by downloading the details of the recording being viewed, such as the acquisition location, commencement time and channel attributes. Next, the application begins to download signal data from the server. By default, the application will attempt to load all

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of the signal data in sequence in the background. A progress bar indicates which data segments that have been loaded. For usability purposes, the data are downloaded on demand, i.e., the recording segment currently in view receives priority. So, if the user moves the viewport to a recording segment that has not yet been downloaded, then the current request is interrupted and a new request is issued starting from the updated viewport location. If acquisition is ongoing, then new data will be periodically arriving on the server. The viewing application detects the presence of new data by polling the server. If a change in the recording duration is detected, then the view is updated and the user is notified. By default, a bipolar montage is applied to the electrode data. Signal rendering colours are applied automatically based on electrode placement, but the the colours are also user-configurable. Three filters are available: a 0.5Hz high-pass filter, a 30Hz low-pass filter and a 50Hz notch filter. Only the notch filter is enabled on all channels by default, but each can be enabled or disabled on a per-channel basis. There are plans to make the filter frequencies adjustable in future versions. An option is provided to disable the rendering of selected channels – a useful feature when artifacts caused by loose electrodes are obscuring the view of other channels. Two viewing modes are provided: browsing and playback. In browsing mode, the user flips instantaneously forwards or backwards through screenfuls of data using buttons or keyboard shortcuts.

VII. CONCLUSIONS

The 5G remote monitoring system presented here provides a technical solution for soliciting expert feedback on data being streamed from critically ill patients when that expert is not physically present in the ICU. The system described applies a general solution to remote EEG monitoring and analysis. EEGs are among the most challenging biosignals to process and display and hence were chosen to demonstrate the capabilities of the remote monitoring system. Other biosignals only require a subset of this functionality in order to be displayed effectively and hence can be readily incorporated. The infrastructure provided has several secondary benefits as it allows engagement in activities such as archiving, data mining, remote collaboration and training. These activities have been identified by other research groups as important. Remote monitoring reduces diagnosis turnaround time, facilitating timely treatment and hence improving patient outcomes. containing suspected seizures, reducing time to diagnosis. The addition of video support is also being considered. Neurophysiologists will often consult the video record, if available, to check for signs of seizures or determine the source of artifacts in the EEG signal. The computational and transmission overheads involved when dealing with video are significantly greater than those for EEG, and must be taken into consideration. However, the approach used for streaming EEG data would apply equally well to video, provided that issues related to patient privacy are addressed. The built in support for streaming video in the Flash platform would facilitate its integration into the viewing application.

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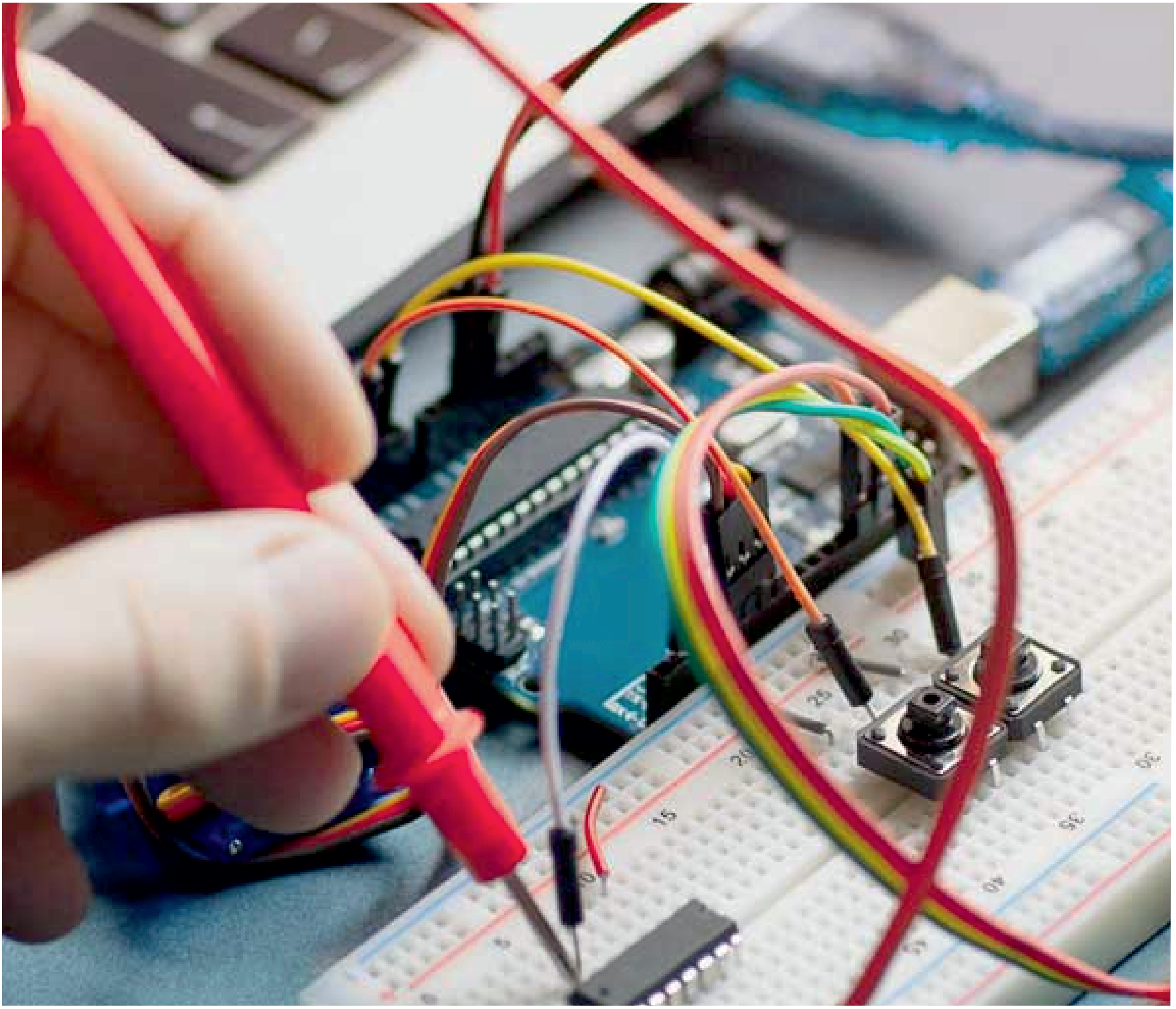

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