Data reduction techniques to facilitate wireless and long term AEEG epilepsy monitoring

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Abstract—Wireless ambulatory EEG (AEEG) monitoring over long periods of time is currently infeasible due to battery limitations and the EEG analysis time required. A detailed comparison of methods for reducing the amount of AEEG data is presented. It is concluded that a discontinuous recording scheme can alleviate both of the above problems. Discontinuous monitoring introduces data interpretation and practical issues which are discussed. With suitable low power algorithm implementations and realistic system expectations such systems are deemed to be feasible.

I. INTRODUCTION

Epilepsy is a well known and high incidence neurological disorder. Approximately two million Americans suffer from the condition [1] while 10% of the population will experience a single seizure during their lifetime [2]. Despite this, accurate diagnosis can be difficult with an estimated 26% of patients being incorrectly identified as having the disorder [3].

Along with clinical evidence, the electroencephalogram (EEG) is a widely used diagnosis tool. Suspected seizures are usually investigated using a 20 minute EEG session [2]. This session is short and up to 50% of epilepsy sufferers will show no abnormal activity [1]. As a result it is also possible to obtain longer term, in-patient, EEG samples typically lasting up to 72 hours. These samples, of course, come with significant monetary and resource overheads that limit the number of patients that can be seen. They also remove the patient from their daily routine which may have been a causative factor in the suspected seizure [2].

These problems are overcome by the use of Ambulatory EEG (AEEG) monitoring. Here, the entire EEG system is portable, allowing monitoring to be carried out over a normal patient day. Whilst this seems an ideal solution a number of drawbacks are still present:

1) There are issues in ensuring that the electrodes remain securely attached for the duration of the testing and also in the social acceptability of wearing head mounted electrodes in public.
2) Systems can weigh up to 1kg, limiting their portability.
3) Up to 32 channels of activity are typically recorded. Each of these channels requires a wired connection from the patient’s head to the recording unit and the compliance of these wires can limit patient movement.
4) Long term recordings generate large amounts of data for storage, approximately 1GB every 24 hours.
5) This data is time consuming for a neurologist to analyse, taking approximately two hours per 24 hour recording [4]. Recording more than 24 hours of data is likely to produce too much information to be easily and quickly analysed by a neurologist, although it increases the likelihood of epileptic activity actually being present during the recording.

The portability problems can be reduced by the use of a wireless AEEG system which removes the connecting wires and reduces the system weight. However, wireless transmission is very power demanding and battery limitations mean that high quality AEEG recordings are currently not feasible over large periods of time. Similarly the large analysis time makes long term AEEG analysis infeasible. Both of these problems can be addressed by the use of suitable online data reduction techniques.

This paper compares such techniques, outlining the trade-offs that are necessary to facilitate wireless systems and also to reduce the amount of data that is presented to the interpreting neurologist. With sufficient performance a wireless system incorporating data reduction could enable long term monitoring, although for this to be successful it is essential that the proposed monitoring scheme can operate using very little power. Section II outlines and compares possible data reduction techniques while Section III discusses the issues that these methods introduce. Finally, Section IV describes an overview of a suitable wireless system that with sufficient performance would be suitable for long term monitoring.

II. DATA REDUCTION MECHANISMS

An AEEG system typically uses up to 32 electrodes mounted on the scalp. At a sampling rate of 200Hz and resolution of 16 bits [5] this produces a data rate of 12.5KBps for the entire duration of the recording, possibly 24 hours. For outpatient use batteries cannot be conveniently checked and replaced making wireless transmission over this period of time impractical. As a result it is necessary to investigate reducing the amount of raw data to be sent. For long term monitoring the reduction methods would also reduce the amount of data presented to the interpreting neurologist. Three principle methods are discussed here, with the results summarised in Table I and discussed in Section II-D.

A. Reduce the quality of the recording

Modern AEEG systems record digitally allowing the sampling resolution and rate to be varied. Reducing these will reduce the data to be transmitted, but also reduce the
recording quality. Clearly minimum values will be required to accurately represent the EEG signal. [6] notes that most EEG signals studied are in the range 0.5–60Hz, although there is also some higher frequency content. A minimum sampling frequency of 120Hz is thus required. Most EEG systems use between eight and 16 sampling bits, and using the lower end of this range would produce the least amount of data.

The data could also be reduced by simply monitoring fewer channels; recording as few as four EEG channels has been shown to be clinically useful [7]. All of these methods, however, reduce the quality of the EEG recording whereas the overwhelming trend over time has been for better sampling rates and improved spatial resolution via more channels. To aid diagnosis future systems should not be designed to go against this trend. The method also does not help to improve the interpretation time.

B. Use compression algorithms on the raw data

There has been interest in recent years in using compression algorithms on raw EEG streams. This has shown good results with approximately a 50% reduction of the raw data being achievable using lossless compression techniques [8] and approximately 85% being achievable when lossy compression is deemed acceptable [9]. These levels are impressive and the schemes should certainly be used where possible. The major barrier to their use is their implementation in suitably low power hardware. Again, however, compression of this kind cannot help to reduce the data that is presented to the neurologist.

C. Do not record a continuous data set

The data presented can be reduced by not recording continuously over the test period. Epileptic EEG traces can be broken down into two phases: ictal (seizure activity) and interictal (spikes and spike-and-waves) [10]. Interictal activity usually contains isolated events along with normal background signals. By recording only the ictal and interesting interictal activity it is estimated that a 90% data reduction can be achieved [4]. (Fig. 1 illustrates an overview of this process.) For comparison, Table I illustrates preliminary results for a wavelet transform based interictal detection algorithm developed from [11] and [12] and analysed with new data as part of this work.

A discontinuous recording method reduces both the data for transmission and reduces the information presented to the neurologist. If the data presented was reduced by 30% or more, significant amounts of neurologist time could be saved and this used to analyse much longer AEEl recordings, increasing the likelihood of a rare epileptic event being present in the recording period [13].

D. Discussion

From Table I it can be seen that the only suitable method for producing recordings that reduce both the data for transmission and analysis is discontinuous monitoring (although low power, real-time data compression is also of significant use to enable wireless AEEl systems). Obtaining sufficient performance may not be trivial (see Section III-C), but it is clear that due to the analysis time required, if AEEl monitoring is to be truly long term (of the scale of months) it will not be possible to analyse all of the data, and so a data selection scheme is necessary. Implementing this online will save both transmission time and analysis time. Care, however, must be taken in the interpretation of the data produced, as discussed below.

III. DISCONTINUOUS PATIENT MONITORING

A. Previous work

Long term, discontinuous monitoring is already available in the electrocardiogram (ECG) field through devices such as the Reveal Heart Monitor [16]. This is an implantable monitor which records 42 minutes of ECG in response to an automated detection or a patient push button event. The device is implanted in an out-patient procedure and allows monitoring for up to 18 months. An epilepsy equivalent would monitor AEEl signals for several months at a time allowing rare epileptic events, which may only occur every six months, to be recorded. Unfortunately, the number of channels involved and the variability of epileptic signals makes such a system considerably harder to implement. Nevertheless, low power, light-weight, wireless, discontinuous AEEl systems are an essential precursor to such a system and require further investigation.

Discontinuous AEEl systems have been considered before, with such a system being implemented in the EEG unit at the Montreal Neurological Institute [17]. This shows that such discontinuous schemes can be practical for standard EEG measurements. However, as considered in [4] and [14], successful discontinuous monitors present both data interpretation and practical issues that need to be addressed, alongside minimising the power requirements for AEEl use.

B. Data interpretation

The first specification issue to overcome is the detailing of exactly what is presented to the analysing neurologist.
The key system point must be that it reduces the amount of raw data that is presented to the neurologist, but does not replace them or their role in diagnosis. There is no hard rule definition of a significant epileptic feature. As a result a discontinuous recording system can only present the neurologist with ‘candidate’ events and they must analyse these to determine their significance in the same way as they would for a continuous AEEG signal. As any system will not be perfect and will have some false positives (FP) the fact that a data section has been recorded should not be taken as proof that activity is present, only that it is likely to be, and so should be checked by a human expert.

Of course, to aid diagnosis it is important that the system records as much true activity as possible. Ordinarily the performance of a detection algorithm is measured via two factors: the sensitivity and the specificity. A precise definition is given in the Appendix, but in brief wanted features must be correctly identified (high sensitivity) while unwanted features or artifacts must not be (high specificity).

However, in a discontinuous recorder which is analysed in the method described above, this is not the case. A high sensitivity is required to actually record the wanted features, but recording unwanted features or artifacts does not carry a ‘negative cost’. These unnecessary recordings will of course reduce the amount of data reduction but they do not affect the AEEG analysis. It is the neurologist, not the data selection algorithm, that performs the specificity stage of rejecting any incorrect features. This is in-line with the system only providing the neurologist with an altered data set, not performing any analysis or drawing any conclusions from the data itself. Overall the recorder can thus be thought of as performing data selection (selecting sections with a high sensitivity for epileptic features) as opposed to event detection (having high sensitivity and specificity).

Indeed some false positives are desirable as they will provide the neurologist with background EEG information which will aid building the overall diagnosis picture. The only issue is ensuring that false positives are rare enough so that data reduction does actually occur. From [14], the maximum rate (if false positives are spaced equally apart in time) that false positives can occur at to ensure that data reduction occurs is given by

$$\text{Max FP per minute} = \frac{60}{\text{Recording window length in seconds}}.$$  \hspace{1cm} (1)

Recording for 70ms (the maximum defined length of an interictal spike [18]) allows 857 false detections to be made per minute. In reality, to include background information the window may be five seconds long allowing just 12 false detections per minute (although false positives may well be grouped together allowing more detections to be made).

Only 12 false positives per minute may seem like a very difficult level to achieve, but in the worst case the system would have too many false detections and will simply record continuously. This is what current systems do, and so a discontinuous system is giving no benefit, but also nothing has been lost. The data selection scheme will have some power overhead associated with it, but in a wireless AEEG the wireless transmission stage will consume by far the most power. Running a low power monitoring stage which can turn off the high power transmission stage, if only for a short time due to numerous false detections, can have significant benefits to the overall power consumption, aiding the practicality of the wireless system. A first generation wireless system thus only needs a modest level of data reduction to begin providing benefits. Further iterations of the monitoring scheme could investigate further false positive rejections with a view to facilitating long term monitoring.

The second potentially significant problem is determining what is an ‘interesting’ event that is actually worth recording. [14] notes that EEG ‘experts’ when asked to mark interictal events on the same EEG recording will often mark noticeably different sections (agreeing anywhere between 0 and 90% of the time). This can affect the found sensitivity of the monitoring scheme as any two experts will disagree over its performance. As noted above, however, a monitoring system

### TABLE I

**Performance comparison of data reduction schemes**

<table>
<thead>
<tr>
<th>Method</th>
<th>Notes</th>
<th>Approximate amount of EEG tested</th>
<th>Lossy?</th>
<th>Reduces analysis time?</th>
<th>Sensitivity(^a) / %</th>
<th>Data reduction / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full recording (baseline)</td>
<td>32 channels, 16 bit, 200Hz</td>
<td>N/A</td>
<td>No</td>
<td>No</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Reduced quality</td>
<td>32 channels, 8 bit, 120Hz</td>
<td>N/A</td>
<td>Yes(^b)</td>
<td>No</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Reduced quality</td>
<td>4 channels, 8 bit, 120Hz</td>
<td>N/A</td>
<td>Yes(^b)</td>
<td>No</td>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>Lossless compression</td>
<td>See [8]</td>
<td>154 data sets</td>
<td>No</td>
<td>No</td>
<td>100</td>
<td>39–62</td>
</tr>
<tr>
<td>Lossy compression</td>
<td>See [9]</td>
<td>8 data sets</td>
<td>Yes</td>
<td>No</td>
<td>100</td>
<td>81–89</td>
</tr>
<tr>
<td>Discontinuous (Gotman)</td>
<td>See [4], [14] and [15]</td>
<td>200 hours</td>
<td>Yes</td>
<td>Yes</td>
<td>Unknown</td>
<td>90–95</td>
</tr>
<tr>
<td>Example CWT method(^c)</td>
<td>140ms recording window</td>
<td>41 hours (400 events)</td>
<td>Yes</td>
<td>Yes</td>
<td>79</td>
<td>94</td>
</tr>
<tr>
<td>Example CWT method(^c)</td>
<td>5s recording window</td>
<td>41 hours (400 events)</td>
<td>Yes</td>
<td>Yes</td>
<td>79</td>
<td>80</td>
</tr>
</tbody>
</table>

\(^a\) See Appendix for definition.

\(^b\) Lossy as intrinsically contains less information than the baseline, although this lost information may not be useful.

\(^c\) Developed from [11] and [12], analysed with new data as part of this work.
Fig. 2. Block diagram of the electronic processing stages required

does not need to reject non-features. The fact that one expert has marked an event shows that it is worth recording even if a second expert then discounts it. This, of course, affects the reported sensitivity of the scheme which can now only be taken as a guide measure. The true performance must be measured by neurologists in terms of the aid to diagnosis, although this can only be done once systems are in place.

IV. SYSTEM OVERVIEW

It has thus been shown that provided the interpreting neurologist is aware that the system does not detect epileptic features exclusively and must be analysed in the same way as current continuous systems, there are clear benefits to a discontinuous AEEG system for facilitating wireless AEEG and possibly longer term monitoring. An overall system outline is shown in Fig. 2. With good design it should be possible to integrate the system shown onto the electrodes giving a system which is very physical small with no presence other than on the head (a typical power source of a hearing aid battery has a diameter of 8mm and weighs 0.8g [19]; the processing electronics may have a comparable size and weight). For a first generation system it is proposed to aim to monitor interictal spikes only. If this can be successfully achieved then suitable work could be carried out to monitor other types of epileptiform activity, and miniaturise the electronics appropriately.

V. CONCLUSION

Wireless, long term, AEEG systems offer greater patient freedom and aid epilepsy diagnosis, but due to power supply and analysing time constraints are not possible with current systems. The data to be transmitted and analysed must be reduced, and this can be achieved by using a discontinuous monitoring scheme. Although care must be taken when interpreting the data provided and low power implementations are needed, first generation systems should be feasible.

APPENDIX

True positives (TP): The number of correct classifications of a feature as a feature.

False positives (FP): The number of incorrect classifications of a non-feature as a feature.

True negatives (TN): The number of correct classifications of a non-feature as a non-feature.

False negatives (FN): The number of incorrect classifications of a feature as a non-feature.

Sensitivity: The probability of a feature being correctly identified, $\frac{TP}{TP+FN} \times 100\%$.

Specificity: The probability of a non-feature being correctly rejected, $\frac{TN}{TN+FP} \times 100\%$.

REFERENCES