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Disruption-Tolerant Wireless Biomedical Monitoring for Marathon Runners: a Feasibility Study

Djamel Benferhat*, Frédéric Guidec*, and Patrice Quinton**

Abstract—Off-the-shelf wireless sensing devices open a wide range of perspectives for tetherless biomedical monitoring. Yet most applications considered to date imply either indoor real-time data streaming or ambulatory data recording. Disruption-tolerant networking is a means to cope with challenging situations where continuous end-to-end connectivity between communicating devices cannot be guaranteed. In this paper we investigate the possibility of using this approach to remotely monitor the cardiac activity of runners during a marathon race, using off-the shelf sensing devices and a limited number of base stations deployed along the marathon route. Preliminary experiments show that such a scenario is indeed viable, although special attention must be paid to balancing the requirements of ECG monitoring with the constraints of episodic, low-rate transmissions.

Index Terms—Wireless disruption-tolerant networking, sensor networking, biomedical monitoring

I. INTRODUCTION

Wireless Biomedical Sensor Networks (WBSN) are a variety of wireless sensor networks (WSN) in which sensors are dedicated to the monitoring of health parameters, such as physiological [1], kinematics [2] and ambient [3] parameters. Such sensors open up new opportunities in health care, as they allow long-term, continuous monitoring of patients in clinical environment, but also that of ambulatory patients at home [4]. In the latter case the cost and inconvenience of regular visits to the physician can be avoided, or at least significantly reduced.

As a general rule one or several lightweight, battery-powered sensors are attached to the patient, and a wireless base station is installed in the patient's surroundings. This base station can be configured so as to store the data received from the sensors. It can also forward these data directly to a remote site, such as a physician's desktop computer or a hospital's monitoring center. In any case, since the sensors are wireless the patient can move freely around the base station, while an endless stream of data flows from the sensors he/she is carrying to the base station. This freedom of movement is however limited by the short transmission range of the wireless sensors. Most sensors implement low-power radio transmission standards (such as Bluetooth or ZigBee), with which actual transmission ranges are usually between a few meters (indoor) and up to a hundred meters (outdoor).

In the most traditional scenario involving wireless biomedical sensors and a base station, it is commonly assumed that the transmission link between a sensor and the base station is continuously available and reliable. Transient link disruptions can be tolerated thanks to protocols implementing an ARQ (Automatic Repeat reQuest) mechanism, yet the general assumption is that frequent, long-term disruptions cannot occur while a patient's health status is being monitored. Although such an assumption can be verified when a patient does not move much around the base station, there are circumstances when the connectivity between sensor and base station can be seriously disrupted by the patient's mobility.

The concept of *Disruption-Tolerant Networking*[1] *(DTN)* has recently been introduced in the literature as a means to cope with challenging situations where continuous end-to-end connectivity in a network cannot be guaranteed [5]. When considering a network where at least some of the nodes are mobile, the general idea is to apply the *store, carry, and forward* principle on these nodes: a node that is temporarily disconnected from the rest of the network can *store* messages for a while in a local cache, in order to *forward* these messages later when circumstances permit. If a node that stores messages is a mobile node, then mobility becomes an advantage as it allows messages to be *carried* physically (and potentially on long distances) before being forwarded to another node. This approach makes it possible to fill the gap between non-connected parts of the network, allowing remote nodes to communicate even though no temporaneous end-to-end connectivity is ever achieved between these nodes.

Applying the store, carry and forward principle in wireless biomedical sensors is an appealing prospect. Instead of being requested to remain constantly close to the base station that is monitoring his/her health status, a patient can occasionally stray away from the base station without interrupting the process of data gathering, nor compromising the integrity of the data. When the wireless link between a sensor and its base station is disrupted, the sensor stores the data it captures in a local cache. When the link is available again, the sensor uploads the content of its cache to the base station, together with new data it keeps capturing in real-time. In variants of this model, several sensors can cooperate in order to forward data to the base station [6], or several base stations can be deployed so that sensors simply need to upload data to the nearest base.

In this paper we consider the technical problems raised by the utilization of the store, carry, and forward principle in wireless biomedical sensor networks (WBSN). To the best of our knowledge this subject has not been investigated much so far, although disruption-tolerant solutions for *non-biomedical* sensor-based applications have already been proposed in the

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[1]The term Delay-Tolerant Networking is also used in the literature, although it is rather used to denote networks where very long propagation delays are the prime concern to deal with (such as interplanetary networks).

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literature [7], [8], [6]. With this paper our main motivation is to confront the possibilities offered by current off-the-shelf sensors with the requirements of a demanding biomedical application, in order to assess if such an application can indeed be implemented using existing devices and technologies. To achieve this goal we deliberately focus on a scenario we consider as a most challenging one: the monitoring of the cardiac activity of runners during a marathon race. The underlying idea is that if disruption-tolerant biomedical monitoring can be performed in such a scenario, then similar solutions can also be designed and implemented for less constrained scenarios.

II. OVERVIEW OF OFF-THE-SHELF WIRELESS SENSOR DEVICES

As a general rule a typical sensor node —or *mote*— is composed of a micro-controller or full-featured CPU, one or several transceiver modules, internal and/or external memory, a power source, and one or more sensing elements. Many off-the-shelf models are dedicated to the monitoring of ambient parameters, so they include built-in sensing elements to capture data such as the ambient temperature, hygrometry, atmospheric pressure, seismic activity, etc.

A survey of off-the-shelf sensors is available in [9]. In our project we consider using SHIMMER platforms as biomedical sensors and TELOS-B sensor platforms as the radio units of our base stations. The characteristics of both kinds of platforms are detailed below.

Crossbow's TELOS-B "mote" platform is an open-source platform designed to enable experimentation in research projects. Its architecture is quite representative of that of most other off-the-shelf sensor platforms. It features an 8 MHz TI MSP430 micro-controller with 10kB RAM, 16 kB EEPROM, 48 kB flash memory (for the firmware), and 1 MB external flash memory (for data logging). The radio module is based on an IEEE 802.15.4/ZigBee compliant CC2420 transceiver, which runs in the 2400 MHz to 2483.5 MHz ISM band and allows data rates up to 250 kbps. Data acquisition is performed on up to 8 channels through a 12-bit AD converter. Programming and data collection can be performed either via a radio link or via a built-in USB interface. Power is provided either by 2 AA batteries or by the USB interface. Note that in our project we plan to use TELOS-B platforms as radio units for base stations, because of their programmability. For a real deployment of many base stations along a marathon route, USB dongles with embedded 802.15.4 transceivers should probably be used instead of TELOS-B platforms, as this would reduce the cost of this deployment.

SHIMMER is an extensible sensor platform that shares many features with Crossbow's TELOS-B platform, although it is most especially dedicated to recording and transmitting physiological and kinematic data [10]. The SHIMMER platform is powered by an integrated Li-Ion battery. It features an 8 MHz MSP430 CPU and two radio transceivers: an 802.15.4/ZigBee compliant CC2420 transceiver, and a WML-C46A class 2 Bluetooth transceiver. A 2 GB micro-SD card provides storage capacity for data logging. Several kinds of expansion modules are available, incorporating physiological sensors such as ECG (electrocardiography), EMG (electromyography) or GSR (galvanic skin response) sensors, as well as kinematic sensors for 3-axis angular rate sensing and 3-axis low field magnetic sensing. Utilization of these modules for biomedical monitoring has been validated experimentally [10].

Like many other sensor platforms the TELOS-B and SHIMMER platforms are driven by TinyOS, a free and open-source component-based operating system targeting wireless sensor networking [11]. TinyOS applications are built in nesC (a dialect of the C language optimized for low memory consumption) out of event-based software components, some of which present hardware abstractions and others higher-level abstractions such as packet communication, routing, sensing, actuation and storage.

III. DESCRIPTION OF THE MARATHON SCENARIO

As mentioned in Section I our objective is to investigate the feasibility of disruption-tolerant biomedical data monitoring in challenged conditions. The scenario we consider as a test case is defined as follows: we assume the cardiac activity of athletes must be monitored using off-the-shelf ECG sensors during a marathon competition. This particular scenario was selected because runners must cover a long distance during a marathon, and that distance clearly exceeds the limited radio range of the low-power radio transceivers available on current sensor platforms. Besides, since runners in a marathon all follow exactly the same route, a number of base stations can be deployed along that route (see Figure 1).

A base station (BS) is typically composed of a processing unit —for example a laptop— that features an 802.15.4 interface, and at least one wired or wireless interface for long-distance transmissions (typically an access to the Internet). The 802.15.4 interface is used to receive data from the sensors carried by marathon runners, and the long-range interface is used to forward these data to a remote site (for example the closest medical aid station, or a physician's desktop, laptop, or smartphone). Data received from the sensors can be processed locally on the BS before being forwarded to the monitoring site, although that is not a requirement.

Ensuring a full coverage of the marathon's route would require a very large number of base stations, so the idea is that a sparse coverage of the route is ensured using only a limited number of base stations, as shown in Figure 1. A disruption-tolerant solution for data gathering must therefore be implemented: as long as the ECG sensor carried by a runner is out of the radio range of any base station, the data captured by this sensor is stored locally in its internal memory. Whenever the runner passes by a BS, a transient radio contact occurs between the sensor and that BS. This contact is exploited by the sensor to upload data to the BS, which in turn can relay these data to the monitoring center. This is a typical illustration of the store, carry and forward principle, since data acquired on a mobile biomedical sensor are stored and carried for a while, before being forwarded wirelessly to another device (in that case a BS).

The implementation of such a scenario might seem to be quite straightforward. Yet the problem is that ECG monitoring
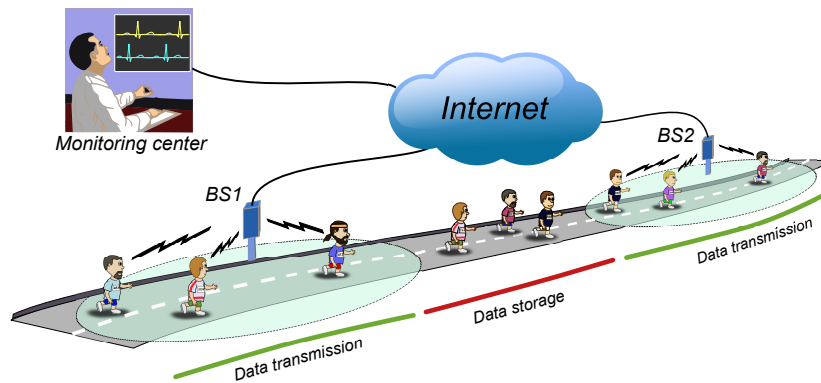
Figure 1.   Illustration of disruption-tolerant ECG monitoring of marathon runners

is a rather demanding application, whereas radio transmissions based on the IEEE 802.15.4 standard can only be achieved on a short range, and with low data rates. The question is therefore to determine if the requirements of ECG monitoring can be balanced with the constraints of episodic, low rate, and short-range transmissions.

In order to answer this question it is necessary to evaluate the exact requirements of ECG monitoring, as well as the possibilities offered by IEEE 802.15.4 transceivers for outdoor data transmission.

IV. REQUIREMENTS AND CONSTRAINTS

A. Requirements of ECG monitoring

The ECG expansion module of the SHIMMER platform provides (Right Arm - Left Leg) RA-LL and (Left Arm - Left Leg) LA-LL input pairs. The (Right Arm - Left Arm) RA-LA pair can then be calculated based on the first two pairs. Sampling is performed on each RA-LL and LA-LL channel by 12-bit A/D converters, and the sampling frequency can be adjusted between 200 Hz and 1 kHz. ECG sampling on two channels therefore produces a continuous stream of data, at a rate that can be adjusted between 4.8 kbps (for 200 Hz sampling) and 24 kbps (for 1 kHz sampling).

ECG monitoring is often performed "in real time" or in slightly deferred time: a physician typically examines the ECG curve as it is produced, or just after it has been produced. Alternatively, ECG data can be recorded during a long period —sometimes several days— on an ambulatory patient, using a device such as the so-called Holter monitor (named after its inventor). In that case the data recorded by that monitor are examined only once the patient comes back to the physician's office.

In our marathon scenario the objective is that ECG data get recorded continuously during the marathon race, and that bundles of data are uploaded whenever possible to the remote monitoring center, which therefore receives frequent updates about the runner's health status. Our assumption is that a reasonable update frequency should be between 5 and 10 minutes. Considering the pace of an average runner this implies that base stations should be placed about 1 to 2 km apart.

B. Possibilities of IEEE 802.15.4 transmissions

IEEE 802.15.4 denotes a standard for low power, low data rate Wireless Personal Area Networks (WPAN). The original version of this standard was issued in 2003. In this version the physical layer is defined to operate on unlicensed ISM bands (868.0-868.6 MHz in Europe, 902-928 MHz in North America, and 2400-2483.5 MHz worldwide), allowing transfer rates of 20 kbps, 40 kbps, and 250 kbps depending on the band considered. Revisions of the 2003 version have been issued since then, that mostly extend the physical layer toward additional frequency bands and advanced modulation techniques.

The SHIMMER and TELOS-B platforms we consider in this project both operate at 250 kbps in the 2.4 GHz band. The question is therefore to determine how much data can be transferred when a marathon runner carrying an ECG-enabled SHIMMER sensor passes by a BS (based on a TELOS-B unit). The 250 kbps transfer rate mentioned in the IEEE 802.15.4 specification is of course the signaling rate —or gross bit rate— on the radio channel. The actual transfer rate available at application level shall of course be significantly lower than that signaling rate.

In order to clarify the potential of 802.15.4 transceivers for data transmissions in our marathon scenario, we conducted a series of preliminary field experiments in realistic conditions. These experiments were conducted outdoor in an open field, using a TELOS-B platform as a base station (BS) and SHIM-MER platforms —with ECG expansion modules— as mobile nodes (MN). Small nesC programs were loaded on the MN and BS, allowing the MN to detect the BS and upload as much data as possible to the BS before getting out of radio range. The detection of the BS by the MN was based on beacon frames broadcast every 2 seconds by the BS. A GPS receiver was used to measure distances and check the runner's speed.

Maximal radio range and contact duration between MN and BS: Our first objective was to measure the distance over which effective data transfers can be achieved between MN and BS in an open field. In practice we observed that connections can be established when both devices are less than 105 meters apart (with a standard deviation of 5 meters). This implies that a BS located on the side of a marathon route should be able to maintain a connection with an ECG-

enabled MN during the time it takes for runners to cover at most a distance of approximately 200 meters (that is, about 35 seconds for fast runners, and between 60 and 80 seconds for average runners).

Maximal throughput of data transfers between one MN and one BS: Data transfers during a contact between MN and BS were performed by producing on the MN an endless stream of full-size data frames (with 114 random bytes in the payload field of each data frame), and counting the number of data frames received by the BS during the radio contact. Data frames were sent in unicast mode, but with acknowledgements disabled so as to avoid retransmissions in that particular experiment.

The experiment was first conducted with a static MN, the MN and BS being only a few meters apart. In such conditions we observed that no data frame was lost during the transmission (even with acknowledgements disabled), but the effective transfer rate did not exceed 55 data frames per second, which corresponds to an application-level throughput of about 50 kbps. This value is surprisingly low compared to the standard's 250 kbps signaling rate, although it is consistent with other results mentioned in the literature [12] and in the TinyOS forum. Indeed it seems that the architecture of the SHIMMER and TELOS-B platforms both present a bottleneck, which lies in the connection between the micro-controller and radio transceiver. Although the CC2420 radio transceiver can send and receive frames at 250 kbps on the radio channel, these frames can only be transferred to or from the micro-controller at a very limited rate. This is an important disadvantage for our marathon scenario, which requires that a single BS be able to receive data streams from several neighbor MN units in the same timespan. Additional experiments are in progress to determine if a USB dongle embedding a 802.15.4 transceiver, used instead of the TELOS-B platform, would show the same 50 kbps limitation.

Impact of contention between multiple MN units: The transmission range and data throughput mentioned above were observed in quasi-ideal conditions, in an open environment presenting no obstacle to radio propagation, little or no radio interference, and with a single MN uploading its data to the BS. In real conditions it can be expected that data transfers between MN and BS will be performed in a noisy environment, with a high level of transmission failures. Moreover several MN may be in the radio range of the same BS at the same time, so this BS shall have to receive and process several data streams during the same timespan.

In order to measure the impact of contention between multiple MN units trying to upload their data to the same BS simultaneously, the experiment was repeated with a runner carrying successively one, two, three, and four MN units. In that case the CCA (Clear Channel Assessment) and backoff functions of the CSMA/CA method were enabled on all platforms in order to avoid collisions whenever possible. Acknowledgements were disabled, though, so we could measure the amount of frame loss. Table I shows the frame loss ratio and cumulated throughput of application-level data received on the BS depending on the number of neighbor MN units. As could be expected the frame loss ratio increases with

# MN units	Frame loss (%)	Throughput (kbps)
1	20	36
2	35	30
3	51	21
4	60	17

Table I

FRAME LOSS AND THROUGHPUT OF APPLICATION-LEVEL DATA RECEIVED BY A BASE STATION DEPENDING ON THE NUMBER OF NEIGHBOR MN UNITS

the number of MN units trying to access the radio channel simultaneously. Conversely, the application-level throughput decreases significantly as the number of MN units increases. This is the consequence of contention between multiple MN units, which yields an inefficient use of the radio channel. This observation suggests that since our marathon scenario requires that a BS be able to deal with several MN units in the same timespan, it should play the role of a channel access coordinator, thus allowing contention-free access to the channel for each MN successively. This is discussed further in the next section.

V. TOWARD A FAIR BALANCE BETWEEN REQUIREMENTS AND TRANSMISSION CONSTRAINTS

Monitoring the cardiac activity of marathon runners is obviously a serious challenge. The preliminary results described in Section IV show that disruption-tolerant ECG monitoring of marathon runners is certainly feasible, but that special attention must be paid in order to keep the demand of ECG monitoring at a minimum while ensuring an efficient use of the wireless medium. Below is a list of options we plan to investigate while working along that line.

A. Reducing the demand of ECG monitoring

Using a low sampling frequency and/or low quantization resolution: ECG monitoring is often performed with a 500 Hz sampling frequency, and by default the SHIMMER A/D converters have a 12-bit resolution. In such conditions the bitrate of the data stream produced by SHIMMER's 2-channel ECG module is 12 kbps. This figure can be reduced significantly by using lower sampling frequency and resolution. For example a 200 Hz sampling with 8-bit samples (on each channel) would only produce a 3.2 kbps data stream. Such parameters may of course alter the quality of ECG data, but signal reconstruction techniques can be used on the receiver side in order to compensate for this low quality [13].

Compressing ECG data before storage and/or transmission: An important constraint here is to implement a compression algorithm that does not exceed the computation power of a SHIMMER platform's micro-controller, such as that proposed in [13]. Our expectation is that by combining low sampling frequency and resolution with efficient data compression the rate of the data stream produced by ECG monitoring on a SHIMMER platform could drop as low as 1 kbps.

Onboard analysis of ECG data: Instead of transferring the whole ECG curve to a remote monitoring site, ECG data could be analyses directly by the SHIMMER platform, which would then simply send reports or alerts to the monitoring center. A recognition module for cardiac arrhythmia is thus proposed in [14], and delineation algorithms for the automatic detection of the major ECG characteristic waves are described in [15]. The algorithms proposed in both papers have a low computational complexity, so they can run on resource-constrained platforms such as the SHIMMER.

B. Getting the most of radio contacts between MN and BS

Using an external antenna on the base station: The TELOS-B platform we used as the BS's receiver has an onboard antenna that is integrated in the printed circuit. The quality of transmissions between MN and BS could definitely be enhanced by using an external antenna on the BS.

Avoiding contention and prioritizing transmissions between neighbor MN units: When several MN units pass close to the same BS during the same timespan, contention between these MN units should be avoided. A possible approach is to implement some channel access coordination method (typically a variation on the TDMA scheme), the BS serving as a coordinator. Upon discovering a BS a MN would first request time-slots from this BS, and the number or duration of these time-slots could be adjusted based on the MN's exact needs. While passing close to the BS the MN could even implement some strategy in order to upload urgent data first, such as the most recent ECG samples, or a subset of all stored samples so the monitoring center can start displaying rough or partial ECG curves before receiving additional data.

Augmenting the capacity of a BS to handle many MN units simultaneously: If the number of MN units that can get in contact with a single BS simultaneously clearly exceeds the capacity of a single 802.15.4 transceiver, then this capacity could be increased by implementing a multi-channel BS. The 2.4 GHz physical layer of the IEEE 802.15.4 standard can operate on up to 16 channels (depending on local regulations). Each base station could therefore include several IEEE 802.15.4 transceivers, each of these transceivers operating on a different channel. Some kind of FDMA multiplexing scheme would then be implemented in addition to the TDMA scheme: upon receiving a beacon of the BS on a predetermined channel (say, channel 0) a MN would contact the BS and be assigned a particular time-slot on a particular channel. Multiplying the number of 802.15.4 transceivers would of course increase the cost of a BS, but this approach would clearly make it possible for this BS to handle a large number of MN units —thus a large number of runners— in the same timespan.

VI. CONCLUSION

Off-the-shelf wireless sensing devices such as the SHIMMER platform open a wide range of perspectives for biomedical monitoring. Yet because of its limited transmission capacity most applications considered to date imply either indoor real-time data streaming, or ambulatory data recording.

With disruption-tolerant networking an intermediate approach can be considered, whereby data are captured and stored continuously on the sensor platform, and transient connectivity with a base station is used opportunistically to upload data to a remote monitoring center.

In order to illustrate this approach we investigate a scenario we believe to be a most challenging one: the ECG monitoring of runners during a marathon race. Preliminary experiments suggest that capturing and transmitting ECG data during a marathon race is feasible using off-the shelf devices, provided the bitrate of data produced is kept at a minimum and data transfers are performed in a most efficient way. In Section V we have listed several options we plan to investigate along that line in the near future.

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