A Real-time Vital Data Collection System for a Group of Persons during a Variety of Sporting Activities in a Large Outdoor Ground

Shinsuke Hara[1], Takunori Shimazaki[1], Takuma Hamagami[2], Yasutaka Kawamoto[2], Hiroyuki Yomo[3], Ryusuke Miyamoto[4], Hiroyuki Okuhata[5] and Fumie Ono[6]

[1]*Graduate School of Engineering, Osaka City University, Sugimoto-Cho, Osaka-Shi, Osaka, Japan*

[2]*Oki Electric Industry Co., Ltd., Bingo-Machi, Osaka-Shi, Japan*

[3]*Graduate School of Science Engineering, Kansai University, Yamate-Cho, Suita-Shi, Osaka, Japan*

[4]*School of Science and Technology, Meiji University, Higashi-Mita, Kawasaki-Shi, Kanagawa, Japan*

[5]*Soliton Systems K.K., Kakuda-Cho, Osaka-Shi, Osaka, Japan*

[6]*Wireless Networks Research Center, National Institute of Information and Communications Technology, Hikarino-Oka, Yokosuka-Shi, Kanagawa, Japan*

Keywords: Real-time Vital Data Collection, Heart Rate, VO2, Location, Wireless Multi-hop Networking, A Variety of Sports Activities, A Group of Persons, A Large Outdoor Ground.

Abstract: We have been developing a wireless vital data collection system named "AccuWiSe," which is workable for a group of persons during a variety of sporting activities in a large outdoor ground in real-time and reliably. Using the second-prototype system, we have conducted an experiment on the 6th of March 2019, where involving 50 subjects, we have successfully collected vital data from 18 subjects making a variety of sporting activities in a sports ground with size of 60m×90m, in data collection rate of 94.9%, once in 2sec regularly, and for 45min continuously. This paper introduces AccuWiSe and demonstrates the experimental results.

1 INTRODUCTION

Reliable and real-time vital signs monitoring is required to promote health and prevent disease/injury for persons during sporting activity. For professional and amateur athletes, it can be also used for evidence-based physical training to improve their performances and identify their talents. We have been developing a real-time vital signs monitoring system for a group of persons during a variety of sporting activities in a large outdoor ground and have named it "Accurate Wireless vital Sensing system (AccuWiSe)." In the development of AccuWiSe, using the first-prototype wireless vital sensor nodes (VSNs) and designed wireless networking protocol, we conducted an experiment on the 26th of February 2018 (Hamagami *et al.*, 2018), where at a data collection node (DCN), we collected the data

- of heart rate (HR), VO2, body surface temperature and humidity, and air temperature and humidity,
- from wireless vital sensor nodes (VSNs) put to the forearms of 22 footballers,
- once in 1 sec during 4×15min football matches,
- in an outdoor football field of 55m×90m,
- using the wireless communication tool with data rate of 100kbps and transmission power of 20mW in the 920MHz band,
- in data collection rate of 97.9%.

The experiment was very successful, but it had three major drawbacks; the first-prototype VSNs were large, the networking protocol was able to accommodate only up to 25 VSNs, and the performance was evaluated only in a single exercise of football match where footballers are likely to randomly spread in the entire ground. According to the feedback and reflection on the system development and the method of performance evaluation, we have developed the second-prototype system and have conducted an experiment on the 6th of March 2019.

In this paper, we introduce AccuWise focusing on its wireless networking technique and show the latest experimental results using its second-prototype system.

Hara, S., Shimazaki, T., Hamagami, T., Kawamoto, Y., Yomo, H., Miyamoto, R., Okuhata, H. and Ono, F.
A Real-time Vital Data Collection System for a Group of Persons during a Variety of Sporting Activities in a Large Outdoor Ground.
DOI: 10.5220/0008066401380145
In *Proceedings of the 7th International Conference on Sport Sciences Research and Technology Support (icSPORTS 2019)*, pages 138-145
ISBN: 978-989-758-383-4

This paper is organized as follows. Section 2 explains the reason to select the 920MHz band and outlines our multi-hop networking protocol in AccuWiSe. Section 3 shows the specifications of the second-prototype system, focusing on its difference from the first-prototype system. Section 4 demonstrates and discusses the experimental results. Finally, Section 5 concludes the paper.

2 WIRELESS NETWORKING TECHNIQUE

2.1 Selection of Frequency Band

We conducted an experiment on real-time vital data collection for 22 footballers during a match in an outdoor football ground (Hara *et al.*, 2013). The main purpose of the experiment was to compare the performance between wireless communication tools in the 920MHz and 2.4GHz bands, so we implemented VSNs which can transmit vital data with the same packet length in the same timings in both frequency bands, where the wireless communication tools were compliant with the ARIB STD-T108 (ARIB, 2011) and the IEEE 802.15.4 standard (IEEE, 2015) with transmission powers of 20mW and 10mW in the 920MHz and 2.4GHz bands, respectively.

As shown in Figure 1 (a), we put the VSNs to the back waist positions of all footballers and also placed 6 data forwarding nodes (DFNs) around the ground. The VSNs broadcast their own sensed data to the DFNs once in 10 sec and the DFNs forwarded their received data to a single data collection node (DCN) directly or through other DFNs. Figure 1 (b) shows the performance on the packet success rate obtained in the experiment. For the wireless communication tool in the 2.4GHz band, even when using 6 DFNs around the ground, the packet loss rate cannot be more than than 75%, on the other hand, for the wireless communication tool in the 920MHz band, when using 1 or 2 DFNs around the ground, the packet loss rate can be more than 95%. This is because the signal in the 920MHz band has a longer transmittable range and is less vulnerable to fading and blocking by human body.

Based on the experimental result, we decided to select the wireless communication tool in the 920MHz band as the one suitable for the real-time vital data collection from a group of persons spread in a large outdoor ground. Note that some real-time vital data collection systems have been commercially available in the market, but they operate in the 2.4GHz industrial, scientific and medical (ISM) band such as WiFi (https://www.wi-fi.org/), Bluetooth (https://www.bluetooth.com/) or Bluetooth Low Energy (https://www.bluetooth.com/). We imagine that a lot of packet losses would occur in them so the lost data might be replaced by the ones previously successfully received, but physical or technical trainers could not notice the fact.

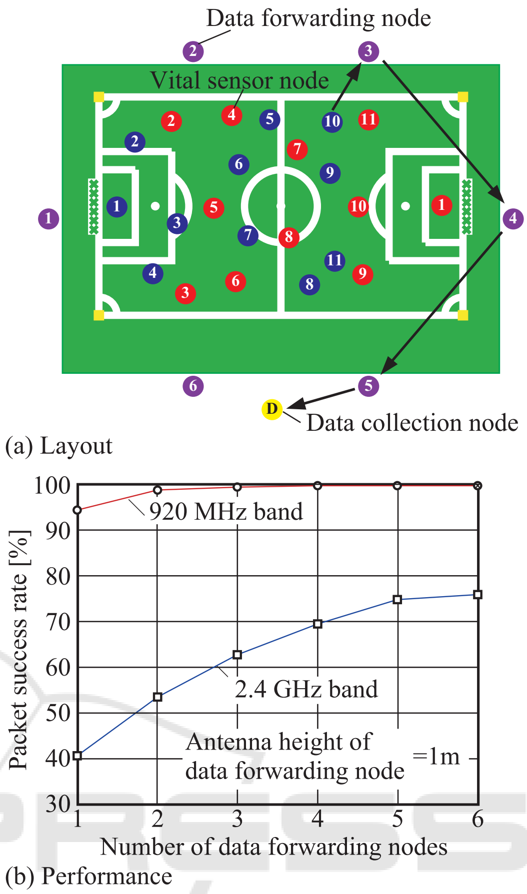


Figure 1: Layout and performance for the broadcast/forward-based vital data collection.

2.2 Multihop Networking Protocol

We decided to use the wireless communication tool in the 920MHz, but when exercisers, namely, VSNs, spread in a large ground, it cannot directly connect them to a DCN, even though it has a longer transmittable range and less vulnerability against fading and blocking. One approach could be to place DFNs or relay nodes in the ground, but through the experiment, we noticed it is troublesome; there is often something wrong with DFN and we need to replace the battery of DFN. Therefore, as shown in Figure 2, we took an approach of multihop data collection through VSNs.

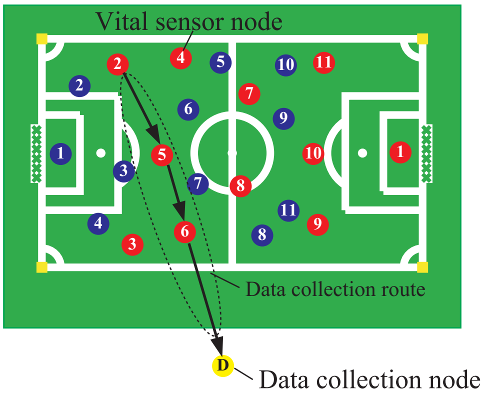


Figure 2: Multihop data collection through VSNs.

We evaluated some ready-made multihop networking protocols such as Ad hoc On-Demand Distance Vector (AODV) (Perkins, Belding-Royer, & Das, 2003), but the experimental packet success rate was terribly low. According to the AODV, VSNs always exchange control packets to discover their neighbors and update their routing tables. When a VSN generates or receives a packet to transmit for a DCN, the VSN forwards the packet to its parent VSN according to its own routing table. When VSNs are stationary, the AODV works well, but when they are in motion, in other words, the network topology is dynamically changing, the AODV does not work well, since when a VSN generates or receives a packet to transmit, its routing table has been already old and invalid. Therefore, we decided to design a multihop network protocol valid for our application.

We designed a flooding/time division multiple access (TDMA) protocol (Hamagami *et al.*, 2018), the principle of which is a superframe-by-superframe Dynamic Source Routing (DSR) (Johnson, Hu, & Malts, 2007). According to the flooding/TDMA protocol, the system operates on two stages such as "pairing stage" and "collection stage."

The pairing stage starts when the switches of the VSNs are on. Each VSN tries to transmit a pairing request packet to a DCN, and when the DCN successfully receives the packet, the DCN transmits a pairing reply packet to the VSN, assigning an identifier number (ID) to it. In the first-prototype system, an distinct ID, which corresponds to the TDMA time slot ID, is assigned to each VSN. Therefore, as explained later, any VSN can freely and solely begin to transmit its data frame in its assigned TDMA time slot as its "slot owner." When all the VSNs have received their pairing reply packets, network association completes.

Figure 3 shows the superframe structure of the flooding/TDMA protocol used in the collection stage, which is composed of a flooding period and a data

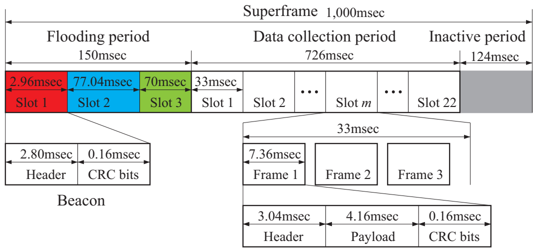


Figure 3: Structure of the superframe.

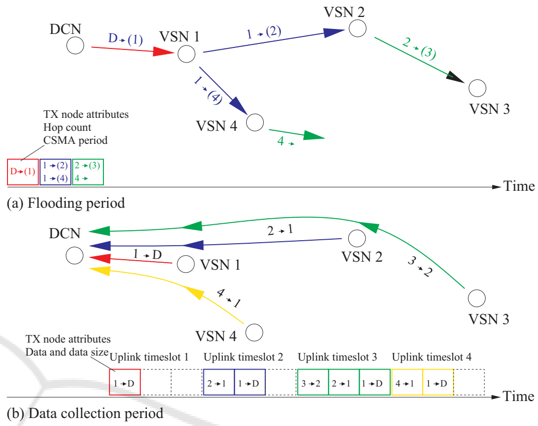


Figure 4: Operation of flooding and data collection.

collection period. The role of the former is to select a suitable parent VSN for each VSN whereas that of the latter is to forward a data frame from each VSN to the DCN through other VSNs without frame collisions. Here, taking into consideration of the ground size and transmittable range of VSN, we limit the number of hops to 3 in the time slot for each VSN.

The communication among the DCN and VSNs is divided into a series of superframes, and the collection stage starts when the DCN broadcasts a beacon. In the flooding period, only the DCN can initiate the transmission of a beacon. When any VSN receives a beacon broadcast by the DCN or another VSN, it re-broadcasts a beacon showing its own node ID and its own hop count in the beacon. In addition, when any VSN receives multiple beacons from other VSNs within a certain period, it measures the received signal strength (RSS) for each received beacon, and it memorizes the node ID which gives the largest RSS as its parent VSN. This is the reason why the second and third slots are longer than the first slot. The maximum number of hops is set to three in the the first-prototype system, so the flooding period is divided into three time slots.

In the data collection period, each TDMA time slot has been assigned to a distinct VSN as its slot owner in the pairing stage, so any VSN can initiate its data frame transmission in its assigned slot. In addition, when a VSN receives a data frame, it unicasts the frame to its parent node.

Finally, Figure 4 shows one operational example of the flooding and data collection periods.

3 SECOND-PROTOTYPE SYSTEM

3.1 Implementation and Experiment of the First-prototype System

One of problems in the development of networking protocol is that there is no repeatability in experiments using real subjects in the sense that we cannot experimentally compare the performances among different protocols at the same time. Therefore, we developed a network simulator which is composed of a channel model set and a mobility model set, and evaluating the performances of different networking protocols changing their adjustable parameters repeatedly in the same environmental situation, we determined the parameters of the flooding/TDMA protocol (Hara *et al.*, 2018), which are shown in Figure 3. And finally, we evaluated the performance of the first-prototype system in experiments involving 22 footballers during 4×15min matches once indoors (first) and twice outdoors (second and third) in 2017 and 2018 (Hamagami *et al.*, 2018). The specifications and experimental results on the first-prototype system are summarized as follows:

- VSN: Size=45mm×44mm×15mm, weight=31g, power consumption=90mA,
- Packet success rate: 98.3% (first indoor, back waist), 92.6% (second outdoor, back waist), 97.8% (second outdoor, forearm), 92.1% (second outdoor, calf), and 97.9% (third outdoor, forearm).

3.2 Implementation of the Second Prototype System

We evaluated the performance of the first-prototype system by the experiments and obtained the successful results, but the system and the method of performance evaluation had three major drawbacks. The first one is that the VSN was composed of two pieces of circuit boards, one of which was equipped with a micro controller unit (MPU) handling several vital sensor devices and the other of which was a ready-made transceiver module also containing an MPU. As a result, the size of the VSN was larger. In addition,

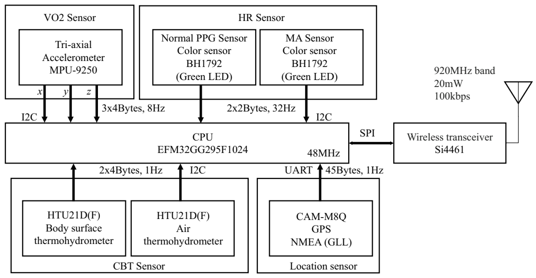
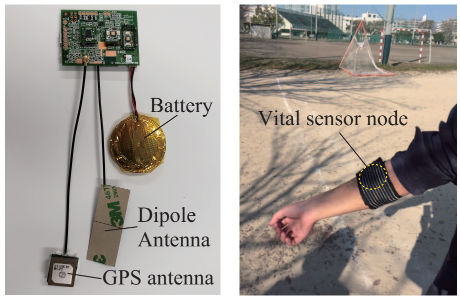


Figure 5: Block diagram of the second-prototype VSN.



(a) Vital sensor node (b) Wearing position

Figure 6: Photos of vital sensor node and its wearing position (forearm).

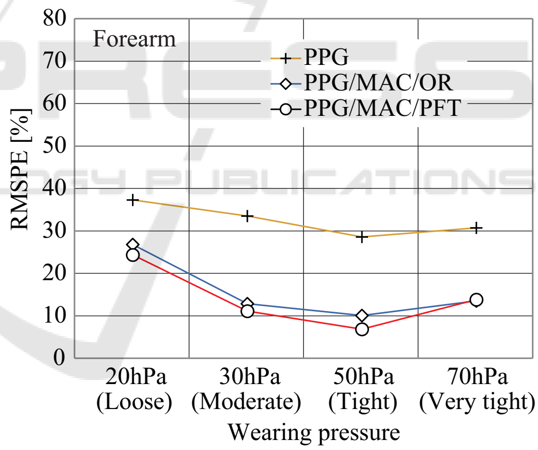


Figure 7: Performance comparison between OR and PFT.

a passive antenna was used for the GPS receiver, so it did not work at all. The second one is that the designed superframe was able to accommodate up to 25 TDMA time slots, in other words, the system was able to accommodate up to 25 persons for vital sensing. Finally, the third one is that we evaluated the performance in a single sporting activity of football, where footballers are likely to randomly spread in the entire ground.

According to the feedback and reflection on the system development and the method of performance evaluation, we have implemented the second-prototype system.

Table 1: Payload format.

Sequence Number	2Bytes
HR	1Byte
Body surface temperature/humidity	4Bytes
Air temperature/humidity	4Bytes
VO2	1Byte
GPS longitude/latitude	4Bytes
Acceleration	12Bytes
Reserved	2Bytes

3.2.1 VSN

Figure 5 shows the block diagram of the second-prototype VSN. A single MPU based on ARM Cortex-M3 handles all the devices, so the VSN is composed of a single circuit board. In addition, some sensor components are changed, so the power consumption is reduced to 70mA (22.2% reduction). On the other hand, we adopt a larger battery (CLB3032) and a larger active antenna (15dB gain) for GPS receiver, so the size of the VSN is not so reduced as 48mm×38×15mm (7.9% reduction) and its weight is 32g including the battery and antenna.

Regarding the wearing position of VSN, we decide to put the VSN to the forearm of person, since the forearm gives the highest packet success rate in the experimental results by the first-prototype system. Figures 6 (a) and (b) show the photos of the second-prototype VSN and its wearing position at a person, respectively.

Furthermore, regarding the signal process for HR calculation, we replace the OR technique by the peak frequency tracking (PFT) technique (Zhang, Pi, & Liu, 2015). Figure 7 compares the HR during sporting activities with different intensities between the OR and PFT techniques, which are obtained by experiments involving 13 subjects. We can confirm the improvement by the PFT in all the range of wearing pressure.

Finally, Table 1 shows the payload format in the data frame.

3.2.2 Multihop Networking Protocol

The second-prototype system is based on the same flooding/TDMA networking protocol as in the first-prototype system, but the superframe structure is changed as an *extended* superframe structure. Figure 8 shows the structure of the extended superframe, where each extended superframe is composed of *n* superframes. To be able to accommodate up to 30 VSN in a superframe, the preamble and payload are condensed while keeping the amount of information the same as for the first-prototype system. According to

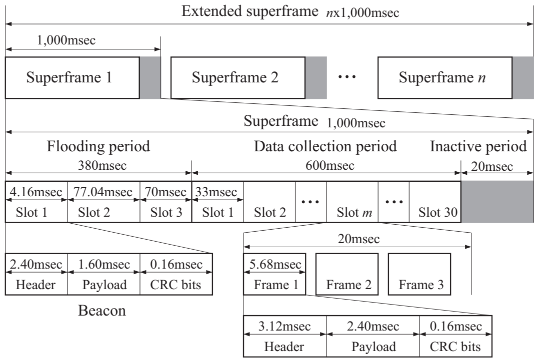


Figure 8: Structure of the extended superframe.

the pairing stage for the extended superframe structure, a DCN first randomly divides a whole VSNs into *n* groups, and then assigns a distinct TDMA time slot in the *n*th superframe to each VSN beloging to the *n*th group.

Table 2: Detail on the experiment.

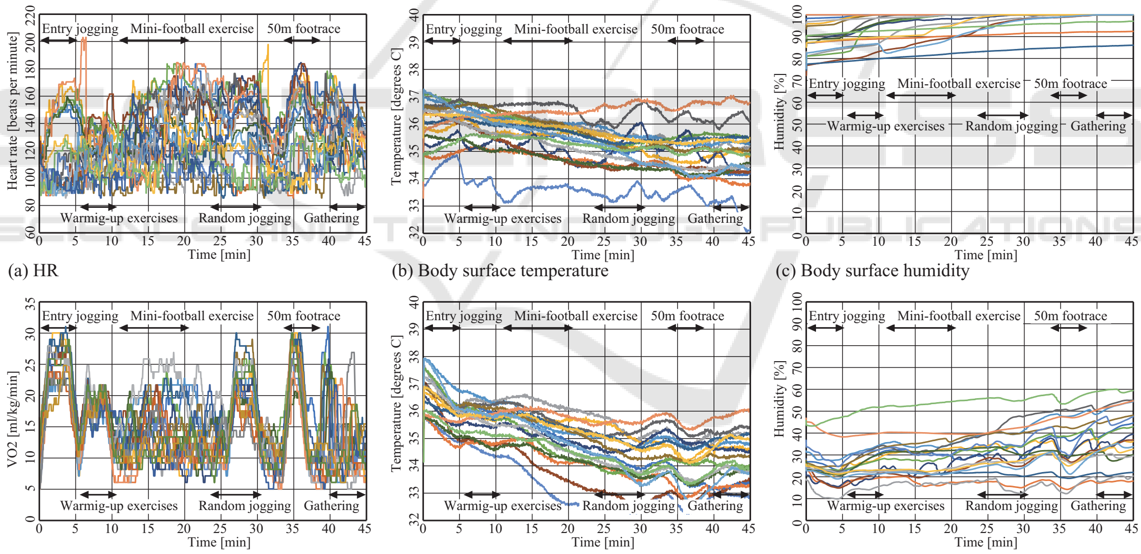
Date	6th of March, 2019
Place	Kita-Yamoto baseball ground
Area	60m×90m
Number of subjects	50
Number of VSNs	18
Number of DCN	1
Sampling rate	8samples/sec
Transmission frequency band	920MHz band
Wireless transmission standard	ARIB-T108
Transmission power	20mW
Transmission rate	100kbps
Duration	45min

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Using the second-prototype system, we have conducted an experiment. To involve 50 subjects in the experiment, we set the parameter of extended superframe *n*=2, so the system was able to accommodata up to 60 VSNs. We had a plan to implement 50 VSNs and 1 DCN before the date of the experiment, but there was something wrong with the batteries and circuits of VSNs, so we were able to finish implementing18 VSNs. Therefore, in the experiment, we put the operable VSNs to the forearms of 18 subjects randomly selected out of 50 subjects. The DCN could as-

(a) Data collection node (b) Panoramic view (c) Entry jogging
(d) Warming-up exercises (e) Mini-football exercise (f) 50m footrace

Figure 9: Photos of the experiment.



(a) HR (b) Body surface temperature (c) Body surface humidity
(d) VO2 (e) Air temperature (e) Air humidity

Figure 10: Sensed vital data for all the 18 subjects.

sign the TDMA time slots in one of the 2 superframes to all the VSNs, but it randomly assigned the TDMA time slots of the 2 superframes, that is, 9 VSNs in one superframe and another 9 VSNs in the other superframe. Table 2 shows the details on the experiment.

In addition, we have designed the protocol of the experiment so as to include a variety of sporting activities, such as uniformly spreading in the entire area, gathering in a localized area, with low and high mobility, with random and coordinated mobility and so on. Table 3 shows the protocol of the experiment for 45min in total period, and Figure 9 shows the photos of experiment.

Figures 10 (a)-(f) show the temporal variations on the HR, VO2, body surface temperature/humidity and air temperature/humidity for all the 18 subjects, respectively. We can see from these figures that the second-prototype system can collect the vital data from all the 18 subjects regularly for 45min. For the HR sensing, we put the Holter monitors to 2 subjects,

Table 3: Protocol of the experiment.

Entry jogging	4min
Gathering into 1 group	1min
Spreading	1min
Warming-up exercises	4min
Gathering	1min
Spreading into 4 groups	2min
Mini-football exercise	10min
Gathering into 4 groups	1min
Resting	2min
Random jogging	3min
Gathering into 4 groups	1min
Dividing into 12 groups	1min
Random jogging	3min
Gathering into 1 group	1min
Resting	2min
50m footrace	6min
Gathering into 1 group	1min
Resting	1min

and we confirmed that the HR sensors worked accurately for them. For the temperature and humidity sensing, the VSN senses the temperature and humidity of the air in the case of VSN through a hole, so they may be affected by those of body surface. However, the air temperature tends to gradually decrease, whereas the body surface temperature tends to keep flat. On the other hand, the body surface humidity tends to earlier saturate (reach 100%) due to sweat by sporting activities, whereas the air humidity tends to gradually increase. Indeed, it began raining around the end of the experiment.

Figure 11 shows the packet success rates for the active 18 VSNs. All the packet success rates are satisfactorily high, the average=94.9%, so we can see that the flooding/TDMA protocol using the extended superframe structure works effectively. In addition, Figure 12 shows the distribution on the number of hops. It is interesting to see that even for the large ground, around 90% of packets reach the DCN directly, but the multihop data collection is essential to make the packet success rate higher.

Finally, Figure 13 focuses the sensed vital data and location for a subject. It is quite natural to see that the HR temporal variation is likely to be synchronized with that of VO2, but there is some disagreement between them around at the beginning of the experiment. We could imagine that it is because the subject was not tired when the experiment started.

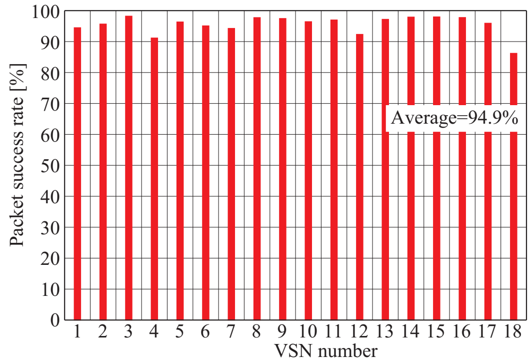


Figure 11: Packet success rate for all the 18 subjects.

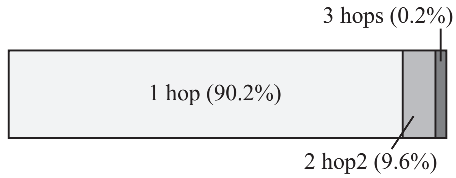


Figure 12: Distribution on the number of hops.

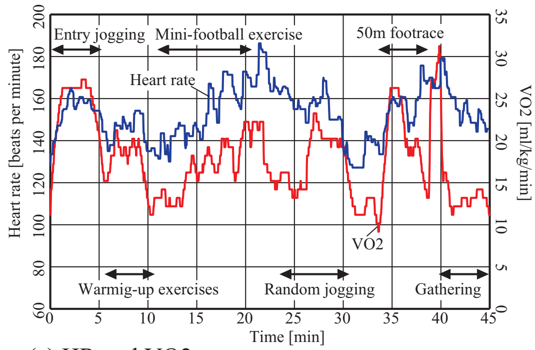
5 CONCLUSIONS

In this paper, after outlining the vital sensing and wireless networking techniques which we have been improving, we showed the latest experimental result on the real-time vital data collection systems for a group of persons during sporting activities in a large outdoor ground. Because of some troubles in implemented vital sensor nodes and batteries, the number of operable vital sensor nodes used in the experiment was not satisfactorily high but we confirmed that the second-prototype system works effectively for 18 persons in a group of 50 persons during a variety of sporting activities for 45min.

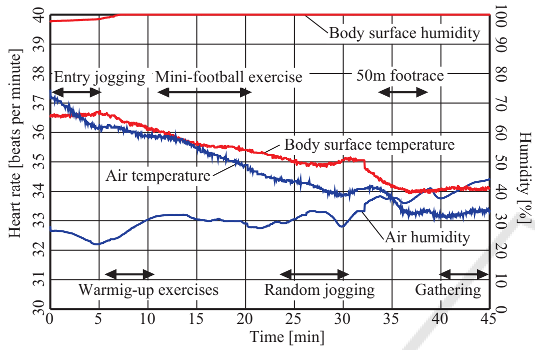
We have not developed a technique to estimate core body temperature using information by wearable vital sensors, so one of our future works includes its development. In addition, we need to accommodate up to 150 persons while improving the packet success rate up to 99.0%, so another of our future works includes the design of a more efficient flooding/TDMA networking protocol based on the extended superframe structure.

ACKNOWLEDGMENTS

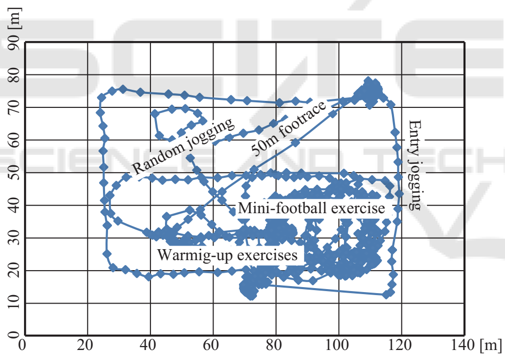
The authors have disclosed no other potential conflicts of interest (COI). In addition, this research was approved by the institutional review board of one of the author's organizations.



(a) HR and VO2



(b) Temperature and humidity



(c) Location

Figure 13: Sensed vital data and location for a subject.

REFERENCES

Hamagami, T. *et al.*, 2018. Wireless Multi-Hop Networking for a Group of Exercisers Spread in a Sports Ground, *Proc. IEEE Healthcom 2018*, pp. 1-6.

Hara, S. *et al.*, 2013. Development of a Real-Time Vital Data Collection System from Players during a Football Game, *Proc. IEEE Healthcom 2013*, pp. 1-5.

Association of Radio Industries and Businesses, 2011. *ARIB STD -T108, version 1.0*.

IEEE, 2015. *IEEE Standard for Low-Rate Wireless Networks 802.15.4-2015*.

Perkins, C., Belding-Royer, E., & Das., S., 2003. Ad hoc On-Demand Distance Vector (AODV) Routing, *IETF, RFC 3561*.

Johnson, D., Hu, Y., & Maltz, D., 2007. The Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4, *IETF, RFC 4728*.

Hara, S. *et al.*, 2018. Performance prediction of wireless multi-hop networks using stored data sets for persons during exercises, *Proc. ICT 2018*, pp. 1-6.

Zhang, Z., Pi, Z., & Liu, B., 2015. TROIKA: A General Framework for Heart Rate Monitoring Using Wrist-Type Photoplethysmographic Signals During Intensive Physical Exercise, *EEE Trans. on Biomed. Eng.*, vol. 62, no. 2, pp. 522-531.