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Performance Evaluation of the VB-TDMA Protocol for Long-term Tracking and Monitoring of Mobile Entities in the Outdoors

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ABSTRACT

The Virtual Beacon-Time Division Multiple Access (VB-TDMA) communication protocol has been proposed in [12] for a growing class of applications which require GPS tracking of autonomous mobile entities in the outdoors, and the long-term continuous monitoring of their contextual information using wireless sensors. Examples include monitoring animal behaviour in their natural habitat over the annual cycle, tracking shipping containers during their life-cycle of transit, loading/unloading and storage, and the handling of high-value packages during transportation. This paper employs simulations to evaluate the network performance of the VB-TDMA communication protocol in a representative scenario involving wild horses attached with collars, each containing a custom-designed platform with a three-axis accelerometer, a GPS module and ancillary electronics and battery, which uploads wirelessly to static base-stations, its position (sensed thrice an hour) and a summary of its activities between uploads. The simulations benefited from movement models derived from real data obtained from a long-term deployment of the collars on wild horses in the Donana National Park in south-west Spain. Comparisons with other MAC protocols have demonstrated the superior performance of the VB-TDMA protocol over a range of metrics for the representative example. An enhanced version of the VB-TDMA protocol - a multi-hop variant - is introduced for low latency requirements and was simulated for an urban scenario of bicycles fitted with sensors for crowd-sourcing spatio-temporal air quality information along the route of travel which is uploaded to the server when within range of static base-stations, for cases where low latency data upload is a requirement to enable access to the latest air quality information.

Keywords

Virtual Beacon, VB-TDMA, TDMA, GPS, wildlife tracking and monitoring, wireless sensor networks, network performance, simulation

1. INTRODUCTION

Recent advances in sensor technology and wireless communication have led to the emergence of battery-powered platforms with sensors, radio, GPS and associated modules for processing, storing and wirelessly transmitting sensor data. There is a class of applications which requires the generation of spatio-temporal data for sensing the context of mobile entities in the outdoors. An important feature is the requirement to extend the battery lifetime because, once deployed, it is expensive to access the entities to replace the batteries. One such example is the tracking and monitoring of the millions of shipping containers moving around the world. The life cycle of the container journey begins when it is loaded with goods and sealed until arrival at the destination warehouse. The container is transported to a port, loaded onto a container ship for the destination port, and unloaded onto a truck trailer or a train for the journey to the final destination. Throughout the journey the containers are tracked and the sensors monitor the handling during the transportation, loading and unloading processes. This data can be uploaded wirelessly to base-stations located on the container ships, ports and warehouses which in turn upload the data to a centralised database. Another example is the self-service, bike-sharing scheme for short journeys in major cities. The bikes are equipped with sensors to measure air quality such as particulate counts for measuring PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ values, and noxious gases such as NO_2 , O_3 , and CO , together with temperature and relative humidity with the sensor values tagged with spatiotemporal information. The bikes are used to crowd-source sensor data during their journeys and the data is uploaded to a central server via base-stations located at the bike-stations.

The contribution of this paper is a comprehensive assessment, using simulations informed by movement models derived from real data of a long-term (12 months) deployment, of the Virtual Beacon-Time Division Multiple Access (VB-TDMA) communication protocol targeted at applications that require GPS tracking of autonomous mobile entities in the outdoors, and monitoring their behaviour using wireless sensors. The implementation of the algorithm in the

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simulation was validated against an actual local deployment over a 17-day period. Sensitivity analysis was performed for choosing parameters such as Time-between-Discovery and Number of Retransmission. The proposed protocol outperforms a selection of other MAC protocols over a range of metrics including the battery lifetime. A multi-hop variant of the VB-TDMA protocol for reducing the data upload latency was simulated for applications when early access to the data is desirable.

In the rest of this paper, Section 2 presents related work in terms of MAC protocols for Wireless Sensor Networks (WSNs), Section 3 gives the background for the test scenario, the simulation environment and the basic asynchronous data upload protocol, Section 4 presents the VB-TDMA protocol, Section 5 describes the experimental validation of the VB-TDMA implementation in the SpeckSim simulator, Section 6 outlines the experiments and presents the results, and, finally, Section 7 gives conclusions and offers improvements for future work.

2. RELATED WORK

The proposed VB-TDMA algorithm [12] is potentially more power efficient than existing MAC protocols for applications involving tracking mobile entities using GPS. It optimises the radio usage to the extent of using it solely for exchanging data packets, without any communication overhead. This is possible by using the GPS time data to generate an internal virtual beacon for precise synchronisation (order of milliseconds). This can be used by all the nodes to synchronise without being in range of any other node, and minimises the time during which the radio is turned on. Also, obtaining the time information from the GPS module does not imply any extra cost in terms of battery consumption, as this information is acquired along with the position coordinates which are essential requirements for the target class of applications [12].

In order to extend the battery life for both the stationary and mobile nodes in the network, it is necessary to keep the components on the hardware platform in sleep mode for as long as possible, and wake them up simultaneously. Due to clock drift, it is not always possible to accurately synchronise the nodes based on their internal clocks during a long-term deployment. Also, in the case of a mobile ad-hoc network in which the nodes are not all in range of each other, the overhead of synchronisation is high, which is counter to the stated objective of keeping the power consumption as low as possible.

The VB-TDMA algorithm is different from other existing MAC protocols, both centralised and decentralised. Time Division Multiple Access (TDMA) protocols are part of the centralised category, where time is divided into slots to allow multiple node communications without causing collisions. For power-constrained devices as in the case of WSNs, the nodes are kept dormant for as long as possible, and are only woken up for the time when they are assigned a communication slot. Since accurate time synchronisation is required, traditional TDMA protocols have a base-station responsible for the coordination, which consumes more power than the other nodes in the network. This is not desired in many WSNs applications, where the nodes have limited energy. Also, in scenarios where nodes can be out of range of the beacon-generating node for extended periods of time, the communication overhead becomes high. Based on the level

of uncertainty of the time synchronisation, the listening window has to be increased, which means that the power overhead increases significantly. An alternative to increasing the window would be to have the desynchronized nodes convert to a non-synchronized method. The VB-TDMA eliminates the need for the base-stations to coordinate the synchronisation of all the nodes, and the exchange of control packets.

Decentralised MAC protocols also do not require a coordinating node in the network, eliminating the problem of unequal power consumption for the nodes. According to [15], this category can be divided into scheduled (e.g. S-MAC [16], T-MAC [4], LMAC [14]) and random-access protocols (e.g. B-MAC [11]). The scheduled ones use time slots similar to TDMA protocols. Their disadvantages are: larger time slots, each node taking on extra functionality by keeping a schedule of its time slots, and the nodes periodically transmitting their schedule to the other nodes in the network, which translate to greater power consumption for long-term deployments of scattered nodes. The low power random-access protocols targeted at WSNs, such as B-MAC, SpeckMAC-B, SpeckMAC-D, WiseMAC [5] and X-MAC [2], employ in-channel sampling by periodically listening for channel activity, turning on the receiver if activity is sensed, and turning it off after receiving a packet or after a timeout.

Whereas the early MAC protocols were designed with energy efficiency in mind, later research has paid attention to multitask support and efficient delivery of bursty traffic, thus prioritising throughput and delay metrics over power consumption. The MAC protocols evolved to solve different classes of problems with the focus shifting from power consumption to throughput and delay [7]. Several multi-channel MAC protocols were proposed such as Y-MAC [9], MC-LMAC [8], MuChMAC [1], the majority of which are less energy efficient than single-channel MACs under light traffic conditions. Incel et. al. [8] present MC-LMAC, a protocol that primarily focuses on maximizing the throughput by using parallel transmissions on multiple channels, avoiding interferences and contention. The sender nodes are allocated time slots which are assigned to specific channels. Kim et. al. [9] present Y-MAC, a multi-channel protocol that aims to achieve both high performance and low energy consumption under diverse traffic conditions. However, the Y-MAC performs better in terms of these two metrics under high traffic conditions. Crankshaft [6] is a single-channel MAC protocol for dense WSNs that aims to achieve high delivery ratios while having low power consumption. It is designed for dense WSNs and its energy consumption overhead is due to employing node synchronisation and channel polling techniques. Tang et. al. [13] present PW-MAC, a protocol based on asynchronous duty cycling that is aiming to reduce the power consumption by having sender nodes predicting the receivers' wakeup times. PW-MAC uses an on-demand prediction error correction mechanism and a prediction-based retransmission mechanism for addressing time challenges and maintaining the energy efficiency while collisions occur.

Given that energy consumption is the primary concern for the proposed class of applications, the choice of other MAC protocols for comparison with the VB-TDMA consists in the ones having the primary aim to minimise energy consumption.

3. BACKGROUND

3.1 Test Scenario

3.1.1 Tracking and Monitoring Wild Horses

The real-world scenario considered in this paper is a 12-month deployment of sensor platforms attached to 32 wild horses, in the Donana National Park, south-west Spain. The requirements for this deployment include collecting GPS positions and light intensity every 20 minutes along with the activity and head orientation over that interval, and uploading this information wirelessly to a network of eight static base-stations. These requirements are demanding, considering the size and weight restrictions (165 grams including the batteries) for mobile sensor platforms. The base-stations were placed on existing towers scattered in the nature reserve, with ethernet connections to a local private data network. The locations of the base-stations were chosen to be near paths expected to be taken by the horses, on the advice of the nature reserve custodians. In order to avoid packet collisions between adjacent base-stations and to provide redundancy, the base-stations operate on one of four channels. Adjacent base-stations operate on different channels, as illustrated in the left-hand side of Figure 1.

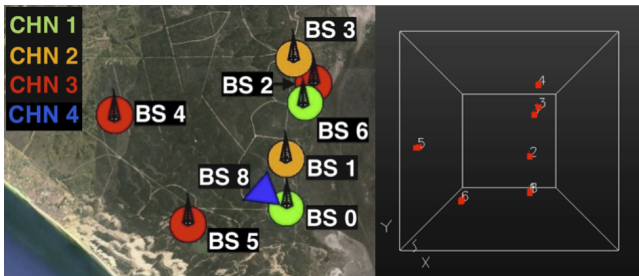


Figure 1: Base-stations deployed in Donana (left); base-stations in SpeckSim (right).

3.1.2 Cyclists Gathering Air Quality Data

A second scenario was simulated for crowd sourcing air quality data from bicycles equipped with air quality sensors (for measuring particulate levels, NO_2 , O_3 , temperature and relative humidity), highlighting the impact of a multi-hop feature in the VB-TDMA protocol. The data collected was uploaded wirelessly to base-stations located at different sites in the university campus. The map of Edinburgh around the university was mapped into the SpeckSim simulator (as shown in Figure 2), with ten mobile nodes representing the student bicycles, and three base-stations for data collection located at the halls of residence. The mobile nodes followed a circuit starting at the halls of residence and visiting way-points representing lecture theatres, a coffee shop, and the gym over a typical 24-hour period. The bicycles could exchange data at any of these locations or in the streets when within range. Since the pollution levels are time-sensitive, the freshness of the data is important for applications that aim to display air quality information as up to date as possible. An example would be an application that chooses a route to a destination which has the best air quality and should use as fresh air quality data as possible by crowd sourcing this information from cyclists.

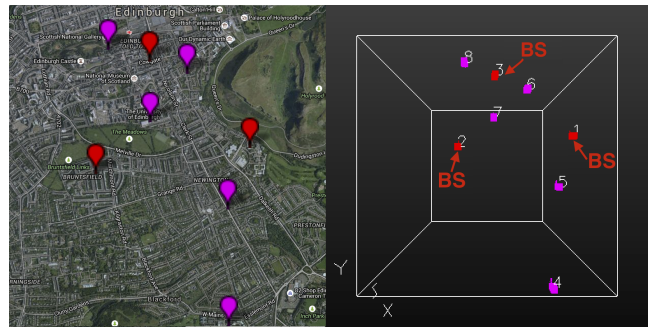


Figure 2: Base-stations and visited locations on the map (left), and in SpeckSim (right).

3.2 The SpeckSim Simulator

The chosen simulation environment is SpeckSim [3], a discrete-event behavioural simulator for modelling computation on networks of sensor nodes. It was developed for algorithmic-level simulations of network behaviour, for different hardware and protocol configurations of static and mobile sensor devices with computational and networking capabilities. Further development has incorporated lower layer communication protocols, radio channel models and modelling of hardware for analysis of power consumption and resource usages. The hardware platform used in the actual deployment in the wild was modelled in SpeckSim, and a summary of the nodes' hardware is presented in Table 1.

Table 1: Summary of Hardware

Prospeckz-5 hardware platform [10]	EFM32 Microcontroller, 128KB RAM, 1MB ROM; NRF24L01+ 2.4GHz radio with RFX2401C amplifier (24dBi end-to-end gain); Sensors: GPS, accelerometer, magnetometer and light.
Mobile node battery	Two Lithium Thionyl Chloride batteries (2x2500mAh)
Base-station battery	Three Lithium Thionyl Chloride batteries (3x2500mAh)

3.3 Asynchronous Data Upload

For this particular horse tracking and monitoring deployment in Donana National Park, the base-station nodes benefited from having access to power and network connection. This being the case, they could have the radio always on to listen for packets thus allowing the use of a basic asynchronous data upload protocol, having the mobile nodes uploading data onto three different channels every 15 seconds. The nodes also have a fast data upload channel on which bursts of up to six packets are transmitted, in order to accommodate other use-cases such as having mobile base-stations either used by biologists, or attached to UGVs (Unmanned Ground Vehicle) or UAVs (Unmanned Aerial Vehicle). On each of the channels a complete set of the data is uploaded, thus offering a 4-way redundancy. The packets are transmitted in chronological order (from the oldest to the newest). Packets are never dropped, and they are resent until the mobile node receives acknowledgement messages for them. This protocol is attractive due to its simplicity.

4. VB-TDMA

The VB-TDMA protocol, initially proposed in [12], was designed to be a low-power communication protocol for tracking applications and requires a hardware platform that contains a GPS module.

TDMA protocols guarantee a time slot for each sender in a network, by relying on an accurate clock to synchronise communications between senders and receivers. When tracking mobile entities over a wide area (several tens of square kilometres), it is required to have their positions marked with time stamps provided by a global clock. These functionalities can be provided by a GPS module, and furthermore, the time provided by the GPS can also be used to synchronise the communication of the sensor nodes.

The VB-TDMA protocol has two phases: one used for determining if a node is in radio range of a base-station, called the Discovery phase; and one that follows the Discovery phase, having the purpose of uploading the gathered data if it was established that the node is in radio range of a base-station, called the Upload phase. For the mobile node, the Discovery phase consists in trying to upload one data packet, and if successful (an acknowledgement message is received), it schedules an Upload slot. If by the end of an Upload slot, the mobile node did not manage to upload all its data, it schedules another Upload slot. This process repeats itself until either the mobile node uploads all its packets or it gets out of radio communication range of the base-station. The base-station node schedules a range of Discovery slots, one for each of the mobile nodes in the deployment, and only activates the Upload slots corresponding to the mobile nodes that uploaded a packet during the Discovery phase. The time interval between the node discoveries should be selected to best suit the application scenarios running the protocol. The time lengths of the Discovery (10ms) and Upload (100ms) slots were chosen to accommodate the speeds of the Nordic Semiconductors nRF24L01+ radio module (15 transmission using this radio were timed to approximately 8ms).

In simulation, the data collection process for the mobile nodes consists in sampling the GPS sensor which returns the position and time, along with sampling the accelerometer and light sensors which only discharge the battery accordingly.

4.1 Multihop Functionality

The multihop functionality in VB-TDMA is intended for mobile nodes to exchange data packets so that those which are rarely or never in range of a base-station can upload their data via other mobile nodes when they come in contact with them. Another two-phase (involving discovery and upload) timing scheme was created for exchanging packets between the mobile nodes, which alternate as senders or receivers depending on the time when they were last in contact with a base-station. In the case of the "wild horses" scenario, the nodes that are not in contact for more than 24 hours with a base-station become senders.

The Discovery and Upload phases on the receiver nodes consist of 10 time slots (Discovery slots - 10ms each; Upload slots - 100ms), i.e., in an optimal situation, a mobile node can collect data from a maximum of ten others during a data exchange following the Discovery phase. The sender node is aware of the time of the Discovery phases (consisting of 10 consecutive Discovery slots) of the receivers, and it

randomly chooses one Discovery slot. After sending one data packet, and assuming the transmission was successful (i.e. an acknowledgement was received), both the sender and the receiver activate the corresponding Upload time slot, in a similar manner to the process of uploading to base-stations.

The packets received from other mobile nodes are stored in a separate queue. When uploading data to other mobile nodes, packets that have not previously been uploaded to base-stations are sent. Also, each node holds a Hash-Set with the sequence numbers of every packet uploaded to other mobile nodes, in order to manage the memory and not upload the same packet twice. In the event that a mobile node fills its memory, it will not accept any more packets from other mobile nodes, and if it does collect more data itself, then the oldest packet belonging to another mobile node is first discarded. This is unlikely to happen in the chosen test scenario, as the flash memory of a node is sufficient to store approximately 10 complete sets of data collected over the course of one year. Packets are only discarded when uploaded to base-stations. When in range, the node first uploads all of its data on the base-station's particular channel, and then continues to upload the data collected from the other mobile nodes.

5. EXPERIMENTAL VALIDATION

The implementation of the VB-TDMA protocol in the SpeckSim simulator was validated against a real test deployment of eight nodes having an accelerated sensor sampling rate. The test deployment was performed on domestic horses belonging to the teaching herd of the School of Veterinary Studies at the University of Edinburgh.

The validation consists in comparing the lifetime of a mobile node from the real deployment to the one of a simulated node having the same protocol configuration and using the corresponding hardware models. Thus, by using the number of GPS positions gathered in its lifetime (until the battery is depleted), we are validating the protocol's implementation. The number of GPS positions gathered is a relevant metric as the GPS module is the major contributor towards the power consumption, with more than 90%.

The validation scenario consists in sampling the GPS module along with the other sensors (accelerometer, magnetometer and light sensor) once per minute, when the clock strikes the zero second. The data is uploaded every minute starting with the 30th second. The algorithm, besides having the accelerated sampling and uploading rates and using only one channel (one base-station was deployed in the test deployment in reality), it works as the one presented in Section 4, having 10ms Discovery slots and 100ms Upload slots.

In reality, a mobile node gathered 23981 packets (GPS locations) before it ran out of battery, and in simulation 23972. The validation test is considered successful, as the difference between the two experiments is extremely low: 0.03%.

6. SIMULATION RESULTS

The results presented in this section are gathered while using different MAC protocols for 12-months deployments consisting of 10 horses and 8 base-stations. The simulations aim to replicate the conditions of the actual wildlife deployment performed in the Donana National Park, Spain. For each simulated scenario, the mobile nodes sample the

GPS module, along with the sensor module which represents the accelerometer and the light sensor, every 20 minutes and are uploading data packets to base-stations every 15 seconds (with the exception of the TDMA protocol which triggers discovery phases every five minutes). Data collected from the actual deployment from 10 horses over a period of 44 days, was used to feed the mobility model and the GPS model for the simulations. This replicates in the simulation the movement of the horses and the time it takes the GPS to acquire a position fix for every location sensed, in order to estimate accurately the wireless network behaviour and the power consumption based on real data. With the exception of the deployment running the asynchronous protocol which had base-stations with mains power having the radio in listening mode continuously, the other deployments used battery-powered base-stations, running on three Lithium Thionyl Chloride batteries (3x2500mAh).

The metrics for the evaluation of the communication protocols were chosen due to their relevance and importance to the class of applications considered in this paper. Table 2 describes the metrics, starting with the most important one, energy efficiency. As the mobile nodes deployed have limited power supply (batteries), the power consumption determines the lifetime of the deployment, and one of the most stringent requirements is that the deployments last for extended periods of time (over 12 months). Even though mobile nodes also store the collected data in their flash memory for retrieval upon collection, it is important for the applications to provide access to the data during the deployment. This led to the need of uploading the data wirelessly to base-stations, and thus the second metric in terms of importance is the volume of data uploaded measured as the number of unique packets uploaded to base-stations during the time of the deployment. The total number of packets created by all the mobile nodes in the 12-month deployment is 262790, this allowing to calculate the percentage of the uploaded data. The third metric is latency (considered as the time between a packet's creation and its first upload to a base-station). The proposed class of applications is not too sensitive to this metric, the latency not posing an issue if it is within the determined acceptable limits set for each specific application. The last metric is network redundancy. The network redundancy is for backup purposes, and having low level of redundancy does not necessarily mean that the number of unique packets collected is lower. The redundancy is inferred by the four-channel structure chosen in the example scenario of tracking and monitoring horses in the wild. This is not a direct property of any one communication protocol, however it does reflect the communication protocol's ability to upload a higher volume of packets. For other scenarios belonging to this same class of applications, having this type of redundancy might not be appropriate.

6.1 VB-TDMA versus Asynchronous

This section compares the performance of the VB-TDMA protocol against the basic asynchronous protocol presented in Section 3. In the case of the deployments presented in this section, for both protocols, the nodes are programmed to have up to 15 retransmissions for a packet in case an acknowledgement is not received for it. After having 15 unsuccessful retransmissions the nodes go to sleep and wake up for the next upload slot to try to upload the same packet (packets are never discarded). The time between adjacent

Table 2: The metrics chosen for evaluation

No.	Metric	Description
1	Energy efficiency	-
2	Volume of data uploaded wirelessly	Total number of unique packets uploaded
3	Latency	Refers to the time between the creation of a packet by a mobile node and its first upload to one of the base-stations
4	Redundancy	Considers the number of packets received 2, 3 and 4 times, due to the use of the four different radio channels

discoveries for the VB-TDMA is 5 minutes and the time between uploads for the asynchronous protocol is 15 seconds. The results are presented in Table 3.

The purpose of this comparison is to show that when having powered base-stations, even one of the most basic designs for a data upload protocol can have good performance.

6.2 VB-TDMA Sensitivity Analysis

A sensitivity analysis helps with choosing the protocol's parameters in order to obtain the best performance for the chosen test scenario. The two parameters of the VB-TDMA protocol are the time between adjacent Discovery phases and the number of retransmissions in case a packet is not acknowledged. The results for varying each of the parameters while keeping the other one constant are presented in Tables 4 and 5. Based on these results, the best tradeoff between power consumption and performance can be achieved with 5 minutes between discoveries and 5 retransmissions.

6.3 VB-TDMA vs Other MACs

As presented in Section 2, most of the more recent MAC protocols (2007-2011) have migrated from having their main concern energy efficiency to being primarily concerned with other metrics such as throughput and delay [6, 9, 8, 1]. Since the class of applications targeted by this paper consists of long-term deployments of sparse (low node density) sensor networks with a low level of traffic, the existing protocols which are not tailored for this type of applications perform poorly. This can be noticed in Table 6. The MAC protocols chosen for comparison were selected from the ones that would have the best chances to perform well in this type of applications, and belong to the category of MACs that have energy efficiency as the primary concern. However, the proposed VB-TDMA protocol is specifically tailored for this class of applications and significantly outperforms the rest.

The chosen protocols for comparison are S-MAC [16] a WSNs MAC protocol that aims to reduce energy consumption and supports self-configuration, SpeckMAC-D [15] a low-power distributed, unsynchronised, random-access MAC protocol for mobile ad-hoc WSNs, and XMAC [2] a WSNs MAC protocol that performs low power listening by employing a shortened preamble approach. The well-known B-MAC [11] was not selected as it was already proven both theoretically and experimentally that it is outperformed by SpeckMAC-D in terms of power consumption [15]. CarrierSenseMac is not part of the energy efficient MACs, but it

Table 3: VB-TDMA versus Asynchronous: 12-month deployment results

No.	Metrics	VB-TDMA	Asynchronous
1	Average percentage of battery left	Mobile nodes: 10.62% - 43days and 9 hours left	Mobile nodes: 8.24% - 32days and 18 hours left
2	Total number of uploaded packets	933995	835636
3	Total number of unique packets (Percentage of the received packets out of the number of expected packets)	262790 (100%)	233844 (88.98%)
4	Average network latency (hh:mm:ss)	02:28:27	02:25:25
5	Packet distribution over BSs		
6	Redundancy percentage 2-level	99.89%	99.87%
7	Redundancy percentage 3-level	91.91%	91.83%
8	Redundancy percentage 4-level	63.60%	26.25%

was selected to highlight a worst-case scenario when having the radio on continuously.

The results show that after 12 months the mobile nodes running the VB-TDMA protocol were left with more than 10% of their battery left, being able to run for another 43 days. In comparison, all the other MAC protocols completely discharged the mobile nodes' batteries before the end of the deployment. Also, the number of packets (unique or including the duplicates) collected by the base-stations while running the VB-TDMA is significantly higher than for the rest of the protocols. XMAC collected the most packets and it still represents less than 50% of the number of unique packets collected using the VB-TDMA.

6.4 The Multihop Functionality

This section presents the results of the VB-TDMA algorithm with the multihop functionality enabled. In the case of the "wild horses" scenario, the multihop feature having the sending/receiving threshold set to 24 hours and the time between mobile-node discoveries set to 5 minutes, lead to a 27% decrease of the latency. This result comes with a meagre 1.81% increase in the power consumption, and the number of unique packets collected by the network did not change. The results can be viewed in Table 7. Enabling the multihop feature had greater effect over the packet collection latency in the case of the student cyclists scenario (see Table 8), where it was lowered by more than 40%, with only a small increase in the power consumption. Even though the multihop functionality reduces the network latency significantly with only a slight increase in the mobile nodes' power consumption, this feature could have an even greater impact on the network performance (in terms of the network's latency and amount of data collected) in scenarios

where mobile nodes are rarely or never in range of a base-station.

Table 7: VB-TDMA Multihop: 12-Month Wildlife Deployment

No.	Metrics	VB-TDMA	VB-TDMA Multihop
1	Average percentage of battery left	Mobile nodes: 10.71%; Base-stations: 61.82%	Mobile nodes: 9.09%; Base-stations: 61.81%
2	Total number of unique packets (Percentage of the received packets out of the number of expected packets)	262790 (100%)	262790 (100%)
3	Average network latency (hh:mm:ss)	02:28:27	01:47:15 (27.75% smaller)
4	Redundancy percentage 2-level	99.89%	99.89%
5	Redundancy percentage 3-level	91.91%	91.63%
6	Redundancy percentage 4-level	63.60%	2.62%

7. CONCLUSIONS

This paper has analysed the performance of the VB-TDMA protocol for the chosen class of application of long-term tracking and continuous monitoring of mobile entities in the

Table 4: VB-TDMA Sensitivity - Time Between Discoveries (Number of Retransmissions = 15)

No.	Time Between Discoveries	1 min	5 min	10 min	25 min	75 min	125 min
1	Average percentage of battery left	Nodes: 10.02%; BSs: 57.4%	Nodes: 10.62%; BSs: 61.82%	Nodes: 10.70%; BSs: 62.37%	Nodes: 10.74%; BSs: 62.70%	Nodes: 10.764%; BSs: 63.04%	Nodes: 10.768%; BSs: 63.15%
2	Total number of uploaded packets	934002	933995	933989	928180	922487	922370
3	Total number of unique packets (Percentage of the received packets out of the number of expected packets)	262790 (100%)	262790 (100%)	262790 (100%)	262790 (100%)	262782 (99.99%)	262734 (99.97%)
4	Average network latency (hh:mm:ss)	02:24:01	02:28:27	02:34:26	02:41:54	03:12:19	03:44:17
5	Redundancy percentage 2-level	99.900%	99.899%	99.899%	99.877%	99.877%	99.883%
6	Redundancy percentage 3-level	91.913%	91.912%	91.911%	91.836%	91.809%	91.818%
7	Redundancy percentage 4-level	63.603%	63.602%	63.601%	61.487%	59.359%	59.363%

Table 5: VB-TDMA Sensitivity - Number of Retransmissions (Time Between Discoveries = 5 minutes)

No.	Number of Retransmissions	1	5	10	15
1	Average percentage of battery left	Nodes: 10.77%; BSs: 63.15%	Nodes: 10.71%; BSs: 61.82%	Nodes: 10.67%; BSs: 61.82%	Nodes: 10.62%; BSs: 61.82%
2	Total number of uploaded packets	922370	933995	933995	933995
3	Total number of unique packets (Percentage of the received packets out of the number of expected packets)	262734 (99.97%)	262790 (100%)	262790 (100%)	262790 (100%)
4	Average network latency (hh:mm:ss)	03:44:17	02:28:27	02:28:27	02:28:27
5	Redundancy percentage 2-level	99.883%	99.899%	99.899%	99.899%
6	Redundancy percentage 3-level	91.818%	91.912%	91.912%	91.912%
7	Redundancy percentage 4-level	59.363%	63.602%	63.602%	63.602%

Table 8: VB-TDMA Multihop: 24-hour Student Cyclists Deployment

No.	Metrics	VB-TDMA	VB-TDMA Multihop
1	Average percentage of battery left	Mobile nodes: 95.63%; Base-stations: 98.23%	Mobile nodes: 95.60%; Base-stations: 98.23%
2	Total number of uploaded packets	14036	14036
3	Average network latency (hh:mm:ss)	00:47:03	0:19:36 (41.65% smaller)

outdoors. The implementation of the protocol in the Speck-Sim simulator was validated against data collected from an actual test deployment aimed at tracking and monitoring horses. The performance of the VB-TDMA protocol was superior to the basic asynchronous protocol (that can only be used in scenarios where the power consumption of the base-stations is not an issue) and to a selection of other low-power MACs (SpeckMAC-D, S-MAC, XMAC), being the only protocol for which the battery of the mobile nodes lasted the full 12-month deployment. A multi-hop variant of the VB-TDMA protocol introduced in this paper was simulated for

a scenario where low data upload latency was desirable, or in cases where some of the mobile nodes in the network rarely or never travelled within range of the base-stations.

Future improvements being considered include extending the VB-TDMA protocol to dynamically change and allocate communication slots between the base-stations and mobile nodes. Also, due to the high power consumption of the GPS module (over 90%), minimising the radio's power consumption any further will not have a great impact on the deployment lifetime. Ideas for reducing the power consumption of the GPS include predicting the location between every two GPS readings using the accelerometer and magnetometer data. Should the accuracy of the predicted location be within acceptable limits, then the GPS sampling can be spaced out, thereby reducing the power consumption and improving deployment lifetimes.

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Table 6: VB-TDMA vs Other MACs: 12-Month Deployment Results

No.	Metrics	VB-TDMA	SpeckMac-D	SMac	XMac	CarrierSenseMac
1	Average percentage of battery left	Mobile nodes: 10.71% - 43 days and 18 hours left; Base-stations: 61.82%	Mobile nodes: 0% (depleted after 190 days); Base-stations: 72.6%	Mobile nodes: 0% (depleted after 77.7 days); Base-stations: 0% (depleted after 146 days)	Mobile nodes: 0% (depleted after 208.5 days); Base-stations: 72.79%	Mobile nodes: 0% (depleted after 9 days); Base-stations: 0% (depleted after 13.6 days)
2	Total number of uploaded packets	933995	277061 (29.66% of VB-TDMA)	48953 (5.24% of VB-TDMA)	168262 (18.01% of VB-TDMA)	6841 (0.73% of VB-TDMA)
3	Total number of unique packets (Percentage of the received packets out of the number of expected packets)	262790 (100%)	98414 (37.44%)	17480 (6.65%)	114480 (43.5%)	6424 (2.44%)
4	Average network latency (hh:mm:ss)	02:28:27	02:22:43	18:19:47	12:24:40	02:04:49
5	Redundancy percentage 2-level	99.89%	89.47%	99.72%	33.70%	3.25%
6	Redundancy percentage 3-level	91.91%	87.39%	80.31%	13.27%	3.23%
7	Redundancy percentage 4-level	63.60%	4.66%	0.01%	2.00%	0%

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