Video Transmission Over A Standards-Based Wireless Multi-Hop Sensor Network

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Abstract—Video transmission combines large quantities of data with real-time requirements, two constraints which are hard to meet in low-power wireless multi-hop networks.

This letter presents experimental results of multi-hop video transmission in an IEEE802.15.4-based wireless network, using a protocol stack based solely on standards which are being finalized.

This practical look allows us to quantify the performance one can expect from such a system, and to underline the areas where further investigation is needed.

1 Opportunities and Challenges

In most applications, Wireless Sensor Networks (WSNs) carry small amounts of sensor data to a sink node, with the duration between two sensor reports which varies from minutes to days. Video transmission sits at the opposite end of the spectrum, and hence puts new challenges on the protocol stack, especially on the Medium Access Control (MAC) layer. This letter shows how Time-Synchronized Channel Hopping (TSCH) – a MAC technology being standardized by the IEEE802.15.4e working group – meets those requirements and can be used for video transmission.

Using a wireless multi-hop network of small low-power embedded devices for transmitting video opens up a new range of possibilities. Following an earthquake, micro autonomous robots could enter a collapsed building and drop off video-enabled sensors to help rescue teams map the rubble and assess the presence of people. Other application areas include surveillance, traffic monitoring and advanced health care [1].

The main challenges are low data rate and multi-hop operation:

- IEEE802.15.4 radios (the *de-facto* standard for such networks) communicate at 250kbps. A 128-byte-long packet (the largest size handled by those radios) hence takes just over 4ms to be sent. Taking into account processing, radio turnaround time and link layer acknowledgments, in practice, a packet is sent every $10ms$ or so, causing the useful data rate to drop to $100kbps$.
- Let's assume a multi-hop path $A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$, with source node A streaming video data to destination node E. One expects every link to be active continuously, i.e. while A sends a packet to B, B is relaying the previous packet to C. Yet, because radios are half-duplex, when A sends to B, B can not send to C, causing the effective data rate to be further reduced to $50kbps$[1].

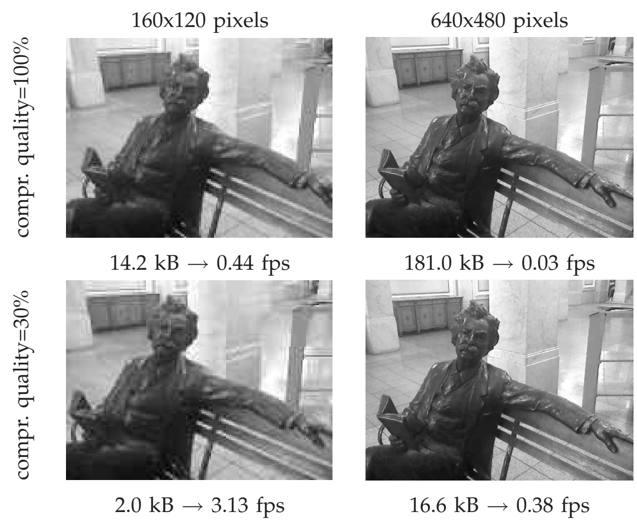

Fig. 1. The quality of the image impacts the frame rate. JPEG compression obtained using the Python Imaging Library (PIL), and an off-the-shelf webcam.

At such low effective data rates, it is important to trade off image size (i.e. compression quality and pixel size) with the frame rate. Fig. 1 illustrates this by taking the canonical case of the network transmitting a succession of JPEG images. It shows how the quality of the images impacts their size, which in turn impacts the maximum frame rate – expressed in frame per second, *fps*. These images were collected using with the Python-based software used in the experiments described in Section 4.

The remainder of this letter is organized as follows.

1. It is sometimes assumed that when A sends to B, C can not send to D or else B will be exposed, causing the data rate to fall to $33kbps$. We show in Section 4 how frequency agile protocols can alleviate that problem.

Section 2 provides an overview of the related work, illustrating how multimedia transmission over WSNs can be tackled at all layers of a communication stack. Section 3 presents a protocol stack composed solely of to-be-finalized standards. This stack couples a Time Synchronized Channel Hopping MAC protocol (to enable video transmission) with 6LoWPAN/IPv6/UDP (to enable seamless integration within the Internet). Section 4 details the experimental setup and discusses the results. The areas that we believe require further investigation are outlined in Section 5, which also concludes this letter.

2 Related Work

Enabling video transmission over WSNs impacts the design of all layers in the protocol stack. In this section, we describe related work from the physical layer up to the application layer.

Several projects have looked at designing video-enabled daughter cards which plug into existing wireless motes. One example is the Cyclops project [2], which proposes a camera daughter card for the mica2 mote capable of performing simple inter-frame compression using an 8-bit Atmel micro-controller. Another, more recent, is the CITRIC project which proposes a camera daughter card for the TelosB mote which uses a 32-bit Intel microprocessor to locally process captured images before sending them through the network [3].

MAC layer design traditionally advantages low-power operation over efficient use of the available bandwidth. As a result, contention-based approaches such as preamble sampling or MAC protocols with common active periods suffer from network collapse at data rates exceeding a few $kbps$ [4]. While suitable for very low-throughput applications, this makes them ill-suited for video transmission.

Most experimental studies have hence opted for single-hop communication [2], [3], or used higher-throughput radio technologies such as IEEE802.11 [5]. To the best of our knowledge, this is the first work to demonstrate multi-hop video communication on a low-power IEEE802.15.4-based network.

The MAC protocol approach used is Time Division Multiple Access (TDMA). Coupled with channel hopping, this technique – called Time Synchronized Channel Hopping (TSCH) – combats external interference and multi-path fading [6]. It has been used in proprietary solutions for industrial WSNs, and is being standardized by the IEEE through its IEEE802.15.4e working group. This letter shows how it can be efficiently used for video transmission.

The way multi-hop routes are established influences the transmission of multimedia streams. Chen *et al.* [7] establish that single path routing is not suitable because of the unreliable nature of the wireless links and the fact that they are bandwidth limited. [7] therefore proposes a geographic routing scheme which allows data to flow over separate multi-hop routes. The performance of the network is evaluated by simulation.

Another important aspect in video over WSNs is compression, which directly impacts the amount of data that needs to be carried. He *et al.* [8] study the impact of video compression on power consumption and the quality of transmitted data. The authors extend the notion of Rate Distortion (R-D) to include Power (P), therefore developing an analytic P-D-R model for data compression over WSNs. Their analysis shows that efficient video compression is crucial in conserving network bandwidth and power consumption.

In traditional MPEG-x or H.26x video encoding schemes, encoding is more computationally intensive than decoding. In a WSN, the encoding source node is usually a mote while the decoding destination is a more powerful computer. The PRISM architecture [9] therefore proposes a compression scheme with can balance the computational load between source and destination. It is evaluated by simulation.

The SensEye project aims at designing a complete camera sensing network [5]. It uses a multi-tier topology (three in this case), where the lower tiers have more motes in the network. The low tier performs object detection and localization, and in turn uses that information to wake up the appropriate (closest) mid-tier motes for higher resolution object recognition, and if necessary wakes up the top tier camera attached to a computer. [5] shows how the hierarchical approach of SensEye consumes less energy than a single-tiered approach by a factor of 33, with only a 6% decrease in sensing reliability. It is to be noted however, that images are not transmitted at the lowest tier, but rather at the upper, IEEE802.11 enabled, tier.

[10] proposes Rate Controlled Variable Bit Rate (RC-VBR), which uses the packet queue size to vary the transmission rate: when the queue gets full, the video quality is reduced . It is coupled with Region Of Interest (ROI) encoding to reduce the amount of data transmitted. Simulation results show an average decrease of 40% in dropped frames, along with a 2.5dB increase in Peak Signal to Noise Ratio (PSNR). At rates of 10kbps, no loss is observed along good video quality. However, the authors observe a sharp decrease in overall network bandwidth, essentially caused by the concepts of hidden and exposed terminals.

The interested reader is referred to [1] which provides an in-depth discussions on important aspects such as collaborative in-network processing, multimedia sensor hardware, and cross-layer design.

3 A Standards-Based Protocol Stack

Major standardization bodies such as the IEEE and the IETF are finalizing standards for Wireless Sensor Networks. Fig. 2 depicts the protocol stack we believe will equip the WSNs of tomorrow. It is based on the IEEE802.15.4 PHY layer, and is composed of IEEE802.15.4e Time Synchronized Channel Hopping at the MAC layer, and IETF "Internet" standards at upper

4	transport	IETF	UDP
3	routing		RPL-*like*
	adaptation		6LoWPAN
2	medium access	IEEE	802.15.4e
1	PHY		802.15.4-2006

Fig. 2. The OpenWSN standards-based protocol stack.

ADV	TXRX	TXRX	SERIAL	SERIAL
0	1	2	3	4

Fig. 3. The IEEE802.15.4e superframe organization used. $L = 5$ slots and $d = 30ms$; the superframe continuously repeats over time.

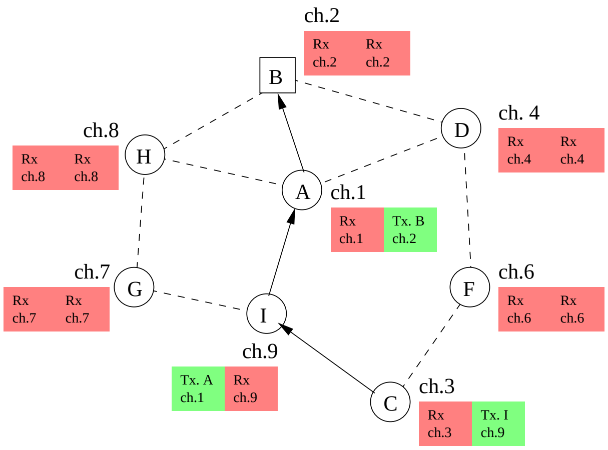

Fig. 4. An example topology, arrows indicate the multi-hop path from C to B. Every node is depicted with the activity it has in its TXRX slots.

layers. IETF 6LoWPAN is the adaptation layer used to compact long IPv6 headers into short IEEE802.15.4 frames.

Note that all of the standards in Fig. 2 – with the exception of UDP – are in the process of being finalized. We have implemented this stack with TinyOS on the TelosB platform as part of Berkeley's OpenWSN project[2].

In IEEE802.15.4e, nodes are synchronized on a common time slotted structure. Slots are grouped into a superframe of length L slots, each slot having a duration d; the slotframe constantly repeats over time. A slot is long enough for a node to transmit a packet to the next hop, and for the next hop node to acknowledge correct reception; a retransmission policy is invoked when no acknowledgment is received. Each transmission can happen on any of the 16 available frequencies on the $2.4GHz$ band. A scheduling algorithm is used to assign each of the $16 \times L$ cells to pairs of neighbor nodes.

We tune the IEEE802.15.4e scheduling algorithm to enable video transmission. Fig. 3 depicts the resulting IEEE802.15.4e schedule, which consists of a superframe of length $L = 5$. The ADV slot is required by IEEE802.15.4e to exchange advertisement packets for neighbor discovery and to keep the network synchronized when no data is exchanged. The SERIAL slots are used for the source nodes to send/receive image data and status information over the serial port (for debugging purposes). TXRX slots are used to exchange the actual video data. When a node receives a packet in slot 1 (resp. 2), it retransmits it in slot 2 (resp. 1).

A hash function is used to translate a node's MAC address into one of the 16 available IEEE802.15.4 channels. A node listens to its own channel and transmits on the channel of the next hop's node. When it has nothing to send in a TXRX slot, a node listens.

Fig. 4 depicts a topology similar to the one used experimentally, and which we use here to illustrate the schedule. Node B is the destination; a node's channel is the rank of its identifier in the alphabet. The RPL routing protocol identifies the most efficient route from C to B to pass through I and A (details about RPL can be found in [11]). The schedule executes as follows. C chooses to send a packet to I on slot 2. I then retransmits that data to A on slot 1 using channel 1. As a result, A can send to B while C send to I (I is not exposed as transmission happen on a different channel), and B receives a packet every slotframe. Note that, as illustrated in Fig. 1, a single image consists of multiple packets.

2. The open-source code and detailed documentation on the different standards is available at `http://openwsn.berkeley.edu/`.

4 Experimental Setup

We show experimentally how a standards-based protocol stack can be tuned to efficiently transmit video, without requiring a paradigm shift. We strongly believe that the cornerstone to tackling this challenge is the Medium Access Control (MAC) protocol.

Similar to Fig. 4, we deploy a network of 8 TelosB motes running the OpenWSN stack. The nodes form a multi-hop network of diameter 3 hops. We attach a computer to the sink node (node B in Fig. 4) to display the received images. Another laptop equipped with a webcam is used to generate images at any of the other nodes in the network. Video is successfully transmitted from any node in the network to the sink node.

By default, we transmit 160x120 pixel gray-scale JPEG images compressed at a 30% compression quality. This yields an average image size of 2.1kB, the equivalent of around 20 packets. The sink receives one packet every superframe, which translates in an image every 2-3 seconds (.33-.5fps).

The energy consumption of a communicating node can be well represented by the ratio of time the radio is on; we call this the network's duty cycle. Table 1 shows the radio on-time for every type of slot. When a node sits idle (it is neither generating nor relaying video), the average duty cycle is 5.8%. On a TelosB mote (which is powered by a pair of $2400mAh$ AA batteries and which consumes 81mW when the radio if on), this translates

Type of Slot	Transmitter	Receiver
ADV	$4.76ms$ on average	
TXRX (w. communication)	$6.86ms$	$7.66ms$
TXRX (w.o. communication)	$0.00ms$	$2.00ms$
SERIAL	$0.00ms$	$0.00ms$

TABLE 1
Radio On-Time as a Function Slot Type

Number of Hops	Image Resolution	Frames Transmitted	Frames Dropped	Frames Corrupted
1	160×120	100	1	7
1	192×144	100	1	3
1	224×168	100	4	10

TABLE 2
Number of Dropped and Corrupted Frames as a Function of Image Resolution

in an average node lifetime of 64 days. A node which relays video (it receives in one of its TXRX slots and transmits in the other), the average duty cycle is 12.9%, which translates into an average lifetime of 29 days.

Latency depends on the number of hops. In one superframe, a mote receives a packet and transmits one. This means that, on average, it takes a packet half the duration of the superframe to travel one hop. Assuming a 2kB image, it is composed of 20 packets. The latency between the moment an image is taken to the moment it is displayed at the receiver is the time to transmit 20 frames ($20 \cdot L \cdot d$), but the time it takes the last packet to travel over 3 hops ($\frac{3}{2} \cdot L \cdot d$), or $3.2s$.

Finally, Table 2 shows the percentage of dropped and corrupted frames as a function of the image resolution.

5 Open Challenges

In this letter we have addressed the topic of Video over Wireless Sensor Networks from a practical perspective. With a fully standard-based network stack, rates up to $.5fps$ were observed along with a success rate above 90%, in a multi-hop environment. It was mainly the TSCH characteristic of the network that allowed us to address issues such as resource constraints and limited channel capacity. Using multiple channels increased the overall bandwidth while making the links more robust.

Many features of the network stack can be improved and are deemed as open challenges. Starting with the physical layer, recent IEEE802.15.4 radios offer a higher $2Mbps$ data rate. This improvement would clearly allow lower latency and higher image resolutions. Unfortunately, higher data rates are not part of the IEEE802.15.4 standard.

Moving up the stack, it should be noted that we have used a standard routing protocol. It could be imagined that, in a dense network, using two (or more) disjoint paths could double the bandwidth of the network (the destination node could receive a packet at every TXRX slot).

Disjoint paths call for a transport protocol capable of handling out-of-order delivery of packets, while end-to-end reliability would result in no frame loss at all. There is a clear need for a transport protocol for WSNs, which could also ensure that MAC resource allocation is performed according to application and transport layer requirements.

Finally, and looking at the application itself, it is noticed that inter-frame compression would make more sense than intra-frame compression since the video sequences in question are mostly static with bursts in changes. It would therefore be preferable to try to identify and compress what changes and later transmit it in order to conserve bandwidth and reduce delay.

References

[1] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, "A Survey on Wireless Multimedia Sensor Networks," *ACM International Journal of Computer and Telecommunications Networking*, vol. 51, no. 4, pp. 921–960, 2007.

[2] M. Rahimi, R. Baer, O. i. Iroezi, J. C. Garcia, J. Warrior, D. Estrin, and M. Srivastava, "Cyclops: In Situ Image Sensing and Interpretation in Wireless Sensor Networks," in *Conference on Embedded Networked Sensor Systems (SenSys)*, San Diego, CA, November 2005.

[3] P. W.-C. Chen, P. Ahammad, C. Boyer, S.-I. Huang, L. Lin, E. J. Lobaton, M. L. Meingast, S. Oh, S. Wang, P. Yan, A. Yang, C. Yeo, L.-C. Chang, D. Tygar, and S. S. Sastry, "CITRIC: A Low-bandwidth Wireless Camera Network Platform," in *ACM/IEEE International Conference on Distributed Smart Cameras (ICDSC)*, Stanford University, California, USA, 7-11 September 2008.

[4] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "MAC Essentials for Wireless Sensor Networks," *IEEE Communications Surveys and Tutorials*, vol. to appear., p. to appear., August 2009.

[5] P. Kulkarni, G. Deepak, P. Shenoy, and Q. Lu, "SensEye: A Multi-tier Camera Sensor Network," in *ACM International Conference on Multimedia*, Singapore, 6-11 November 2005, pp. 229–238.

[6] T. Watteyne, A. Mehta, and K. Pister, "Reliability Through Frequency Diversity: Why Channel Hopping Makes Sense," in *6th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*, Tenerife, Canary Islands, Spain, 26-30 October 2009.

[7] M. Chen, V. C. M. Leung, S. Mao, and Y. Yuan, "Directional Geographical Routing for Real-Time Video Communications in Wireless Sensor Networks," *ACM Computer Communications*, vol. 30, no. 17, pp. 3368–3383, November 2007.

[8] Z. He and D. Wu, "Resource Allocation and Performance Analysis of Wireless Video Sensors," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 16, no. 5, pp. 590–599, May 2006.

[9] R. Puri, A. Majumdar, P. Ishwar, and K. Ramchandran, "Distributed Video Coding in Wireless Sensor Networks," *IEEE Signal Processing Magazine*, vol. 23, no. 4, pp. 94–106, July 2006.

[10] A. Zainaldin, I. Lambadaris, and B. Nandy, "Adaptive Rate Control Low bit-rate Video Transmission overWireless Zigbee Networks," in *Internationl Conference on Communications (ICC)*. Beijing, China: IEEE, 19-23 May 2008.

[11] *RPL: IPv6 Routing Protocol for Low power and Lossy Networks*, ROLL IETF Internet-Draft, 8 March 2010, draft-ietf-roll-rpl-07 [work in progress].

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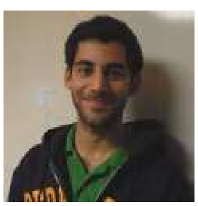

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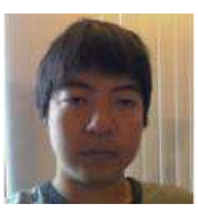

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