A Realistic Energy Consumption Model for TSCH Networks

Xavier Vilajosana, *Member, IEEE*, Qin Wang, Fabien Chraim, Thomas Watteyne, *Member, IEEE*, Tengfei Chang, and Kristofer S. J. Pister

***Abstract*— Time slotted channel hopping (TSCH) is the highly reliable and ultra-low power medium access control technology at the heart of the IEEE802.15.4e-2012 amendment to the IEEE802.15.4-2011 standard. TSCH networks are deterministic in nature; the actions that occur at each time slot are well known. This paper presents an energy consumption model of these networks, obtained by slot-based "step-by-step" modeling and experimental validation on real devices running the OpenWSN protocol stack. This model is applied to different network scenarios to understand the potential effects of several network optimization. The model shows the impact of keep-alive and advertisement loads and discusses network configuration choices. Presented results show average current in the order of 570 μA on OpenWSN hardware and duty cycles 1% in network relays in both real and simulated networks. Leaf nodes show 0.46% duty cycle with data rates close to 10 packets per minute. In addition, the model is used to analyze the impact on energy consumption and data rate by overprovisioning slots to compensate for the lossy nature of these networks.**

***Index Terms*— IEEE802.15.4e, synchronization, wireless sensor networks, duty cycle, energy consumption, TSCH.**

I. Introduction

TIME Slotted Channel Hopping (TSCH) mesh networks are becoming central for wireless industrial deployments as they are able to achieve 99.999% reliability [1] with minimal power consumption. Standards such as WirelessHART [2], ISA100.11a [3] and IEEE802.15.4e [4] are rooted in the TSCH medium access technique. In a TSCH network, nodes are synchronized, and time is split into time slots, each typically $10ms$ long. Time slots are grouped into a slotframe which continuously repeats over time.

The network's communication schedule instructs each node what to do in each time slot: send to a particular neighbor, receive from a particular neighbor, or sleep [5], [6]. Channel diversity is obtained by specifying, for each send and receive slot, a channel offset. The same channel offset is translated into a different frequency on which to communicate at each iteration of the slotframe. The resulting channel hopping communication reduces the impact of external interference and multipath fading, thereby increasing the reliability of the network [7].

All nodes in the TSCH network are synchronized. Because communication occurs at a well-defined times within a time slot, the sender nodes know exactly when to transmit. If the sender and receiver nodes were perfectly synchronized, the receiver node would turn its radio on at exactly the instant when the transmitter starts emitting. The sender's and receiver's radio would be on only for the duration of the packet being transmitted. After the transmission of a packet, both nodes can switch their radios off to save energy or sleep a few milliseconds before repeating the same process in order to receive/transmit an acknowledgment (ACK). This simplistic scenario is the optimal solution in terms of energy consumption that can be achieved in a communication between two nodes, since it minimizes the time during which the transceivers are on.

However, as clocks between neighbor nodes in a network drift ($30ppm$ relative drift is a typical value [8]), a small "guard time" is required at the receiver end to account for relative desynchronization [9]. Acknowledgments follow a similar scheme: a guard time is introduced around the ideal reception moment.

Although the wireless medium is lossy in nature, TSCH networks are deterministic in their scheduling. The energy consumed by a node can be modeled precisely, by profiling the actions that are carried out during each slot. The aim of this article is to present an energy consumption model for TSCH networks, and to analyze the impact of control signaling and the communication schedule on this energy consumption.

Kohvakka et. al. [10] model the energy consumption of the legacy IEEE802.15.4-2006 MAC protocol operating in slotted (beaconed) mode. A similar model is later used to predict the energy consumption per received bit as a function of

Manuscript received September 6, 2013; accepted October 2, 2013. Date of publication October 10, 2013; date of current version December 5, 2013. This work is based in parts on work performed in the framework of the projects CALIPSO-288879, OUTSMART-285038, RELYONIT-317826 and SWAP-251557, which are partially funded by the European Community. The work of X. Vilajosana was funded by the Spanish Ministry of Education under Fullbright-BE Grant INF-2010-0319. The associate editor coordinating the review of this paper and approving it for publication was Prof. Kiseon Kim.

X. Vilajosana is with BSAC, University of California, Berkeley, CA 94720 USA, and also with the Universitat Oberta de Catalunya, Barcelona 08035, Spain, and also with Worldsensing, Barcelona 08013, Spain (e-mail: xvilajosana@eecs.berkeley.edu).

Q. Wang is with BSAC, University of California, Berkeley, CA 94720 USA, and also with the University of Science and Technology, Beijing 100083, China (e-mail: wangqin@ies.ustb.edu.cn).

F. Chraim and K. S. J. Pister are with BSAC, University of California, Berkeley, CA 94720 USA (e-mail: chraim@eecs.berkeley.edu; pister@eecs.berkeley.edu).

T. Watteyne is with Linear Technology/Dust Networks, Hayward, CA 94544 USA (e-mail: watteyne@linear.com).

T. Chang is with the University of Science and Technology, Beijing 100083, China (e-mail: tengfei.chang@gmail.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSEN.2013.2285411