Is Bluetooth suitable for large-scale sensor networks?

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Abstract

Bluetooth is presently the object of much hype by the consortium of large corporate organizations. Bluetooth is developed for local small area networking. It is a technology for replacing the mess of wires that interconnect the electronic gadgets that are widely used. More than a cable replacement technology, it is expected to make a huge impact in ad hoc networking domain. A number of questions remain unanswered regarding the practical utility of Bluetooth in large-scale ad hoc networks. In this paper, we discuss some of the issues involved in using the Bluetooth technology in large-scale distributed sensor networks.

1. Introduction

Networking and computing technologies are becoming advanced enough to enable a wealth of diverse applications that will drastically change our everyday life. Sensor networks [1-9] are becoming a fairly hot area of research where the main focus is the development of networking technologies that support potentially thousands of sensors placed in a chosen environment. A number of applications exists for sensor networks. In the commercial sector, transportation and agriculture are sectors that will benefit greatly from increased surveillance. Personal and institutional security can also apply this research directly to their sectors of activity. Other possible applications exist in radiology, medicine, and manufacturing. Video-based sensor networks [10,11] can be used for a great number of applications that would undoubtedly revolutionize the way we go about our day-to-day life.

National defense relies on accurate Intelligence, Surveillance and Reconnaissance (ISR). Using a large number of small inexpensive sensors increases the dependability of ISR systems at a reasonable cost. Large numbers of redundant sensors decrease the vulnerability of the system to failure. On the other hand, the ability to combine information becomes important. Otherwise, the network will not have sufficient bandwidth and human decision makers will not be able to make timely decisions.

Sharing information requires a suitable communication technology, which preferably should be wireless and nodes must be able to communicate in an ad hoc fashion and without the help of a background infrastructure. Moreover, the communication technology must be robust, scalable, and capable of efficiently using the limited energy of the autonomous devices. More recently, developments in the wireless technologies have enabled ‘anywhere, anytime access’ to information over wireless medium.

Bluetooth [12-37] is an emerging communication standard that provides ad hoc configuration of master/slave piconets including eight active units at most. It supports spontaneous connections between devices without requiring a priori knowledge of each other. Its normal transmission range is 10 meters and optionally it can be extended up to 100 meters. A Bluetooth chip is designed to replace the cables by transmitting information normally carried by the cable at a special frequency to a receiver Bluetooth chip, which will then give the information received to a computer, phone or any other device.

Because the technology can be contained within a single CMOS [38] chip, it is ideal for inclusion in small mobile devices. For example, you can use a headset that is connected via Bluetooth to your mobile phone without having to physically connect the two or even without having to take your phone out of your briefcase, since the two do not have to see each other in order to connect (as with infrared connections).

Commercial Bluetooth solutions are available as fully self-contained transceiver modules and they are designed to be used as add-on peripherals. They feature an embedded CPU, different types of memory, as well as base band and radio circuits. The modules offer a generic Host Controller Interface to the lower layers of Bluetooth protocol stack while the higher layers of the protocol and applications must be implemented on the host system. In this work, we analyze the utility of Bluetooth in large-scale sensor networks.

The rest of the paper is organized as follows. Section 2 provides an overview of Bluetooth. We describe the issues with the Bluetooth technology in Section 3. Section 4 proposes solutions to some of the issues. After discussing the viable alternatives in Section 5, we conclude in Section 6.

2. Bluetooth Overview

The Bluetooth system operates in the worldwide unlicensed 2.4 GHz Industrial-Scientific-Medical (ISM) frequency band [39]. To make the link robust to interference, it employs a Frequency Hopping technique, in which the carrier frequency is changed at every packet transmission. Two or more Bluetooth units sharing the same channel form a piconet. To regulate traffic on the channel, one of the participating devices becomes a "master" of the piconet, while all other units become "slaves." With the current Bluetooth specification, up to seven slaves can actively communicate with one master. In order to extend the reach of these networks, several piconets can then be linked together in what are called scatternets.

The connection point between two piconets consists of a Bluetooth unit that is a member of both piconets. A Bluetooth unit can simultaneously be a slave in multiple piconets, but be a master in only one, and can transmit and receive in only one piconet at a time. So, participation in multiple piconets has to be on a time-division multiplex basis. The Bluetooth system provides full-duplex transmissions using a slotted time division scheme where each slot is 0.625ms long. Master-to-slave transmission always starts in an even-numbered time slot, while slave-to-master transmission always starts in an odd-numbered time slot. An even-numbered time-slot and its subsequent odd-numbered time-slot together are called a frame. There is no direct transmission between slaves in a Bluetooth piconet. Transmission is only between a master and a slave, and vice versa.

Each Bluetooth unit has a globally unique 48-bit address. This address is permanently assigned when the unit is manufactured. In addition to this, the master of a piconet assigns a local active member address to each active member of the piconet. The active member address is 3-bit long, dynamically assigned and reassigned, and is unique only within a single piconet.

In order to establish new connections the procedures namely inquiry and paging are used. The inquiry procedure enables a unit to discover the units that are in range, and their device addresses and clocks. With the paging procedure, an actual connection can be established. Only the Bluetooth device address is required to set up a connection. Knowledge about the clock will accelerate the setup procedure. A unit that establishes a connection will carry out a page procedure and will automatically become the master of the connection.

For the paging process, several paging schemes can be applied. There is one mandatory paging scheme that has to be supported by each Bluetooth device. This mandatory scheme is used when units meet for the first time. Two units, once connected using a mandatory paging/scanning scheme, may agree upon an optional paging/scanning scheme.

The default state of a Bluetooth unit is *standby*. In this state, the unit is in a low-power mode, with all components but the internal clock shut off. In *standby*, there can be no connections open. While there is an active connection to a Bluetooth unit, it is said to be in *connect* state.

In *connect* state, Bluetooth knows four different power modes: *active*, *sniff*, *hold*, and *park*. In *active* mode, the Bluetooth unit actively participates on the channel. Data transmission can start almost instantaneously, but at the expense of increased power consumption compared to the remaining three modes. When low-power operation is favored over short response times, units can make use of one of the three power saving modes *sniff*, *hold*, and *park*. All low-power modes reduce the duty cycle of different units within a piconet. In *sniff* mode, slave units listen in on the channel only at specific times agreed upon with the master. Hence, transmissions can only start at these times. The connections of a piconet can also be put on *hold*. In *hold* mode, every participant, including the master, can take some time off for sleeping. Prior to entering *hold* mode, master and slaves agree on a time when to return to active mode again.

The time off can also be used for conducting other business, such as attending other piconets, or scanning for other units. The park mode is a special mode for slaves that do not need to participate in a piconet, but nevertheless wants to remain connected in order to avoid going through the connection establishment procedure again. Parked slaves do not count as active piconet members. In addition to the eight active members there may be up to 255 slaves parked within a piconet.

3. Bluetooth Issues

While there is no doubt that Bluetooth has many uses, connecting so many devices to phone systems and/or the Internet could pose serious problems of bandwidth and costs. Bluetooth works in the 2.4 GHz ISM radio band [39]. This band is unlicensed for private and already tends to be crowded. So, numerous Bluetooth devices might end-up experiencing serious interference problems. Also, the range and speed limitations might make it unsuitable for large-scale sensor networks. Bluetooth technology broadcasts data over nearly a 10 meter radius. The range can be extended to 100 meters but that requires high power devices. The throughput is 1 mbps but with the overhead it is around 722 kbps only.

3.1. Scalability Issues

The ability to link only the eight nodes of a piconet will in most cases be inadequate to set up densely connected sensor networks. Communication with more than eight nodes at the same time will require some sort of time multiplexing, where additional nodes have to be parked and unparked repeatedly. Setting up additional piconets instead will still require gateway nodes to alternate between their respective piconets, since Bluetooth supports a unit to be active in only one piconet at any given time.

Setting up additional piconets in the same area might also cause some interference. Since the piconets in an area do not coordinate their frequency hopping, the communications in different piconets might randomly collide on the same frequency. If there is a collision on a particular channel, those packets will be lost and should be re-transmitted. So, the more the number of piconets in an area, the higher the possibility for collision and it causes more re-transmissions which leads to a fall in the data rate.

In large-scale sensor networks, applications will most likely need slave-to-slave communication whereas communication in piconets must always be conducted between the master and the slave.

Two slaves must always involve the master node in order to communicate, thus increasing both traffic and energy consumption. Alternatively, one of the slaves could switch roles with the current master, or even set up an additional piconet altogether. Both solutions incur substantial communication and configuration overhead.

3.2. Issues in Connection Establishment

The complexity of the connection establishment procedure stems from the fact that hosts use different hopping sequences before a connection is established. The set-up delay is also affected by the requirement of low-power consumption and the possible connections that hosts may already have. The delay introduced by the procedure may impose constraints on sensor networks.

3.3. Increased Delay

As described in the previous section, inquiry procedure can be used to discover which other Bluetooth units are within the communication range. The Bluetooth inquiry model in general seems to be geared toward settings where a dedicated unit is responsible for discovering a set of other units, e.g. a laptop computer periodically scanning for periphery. Also, in the laptop setting described above, a delay of several seconds for connection establishment would be tolerable. However, in a large scale distributed sensor networks, we expect nodes to be mobile and two Bluetooth devices traveling at a moderate speed could already barley set up a connection before moving out of communication range again. The lengthy connection establishment effectively prevents the use of Bluetooth in fast-moving settings.

3.4. Privacy Concerns

The inquiry message broadcast by an inquiring unit does not contain any information about the source. Instead, the inquired unit gives away information required for connection establishment, such as the unique device id, in the inquiry response. Thus the inquired unit must reveal information about itself without knowing who is inquiring. This inquiry scheme may become a privacy concern in the sensor networks.

3.5. Power Consumption

Finally, because of power consumption, Bluetooth's inquiry is probably less suited for low-power nodes that have to scan their surroundings frequently to discover new nodes or background services. Centralized control of the piconet as well as the asymmetric nature of inquiry and connection establishment puts the burden of expending power onto a single device. Low-power modes may help but they do not apply to every situation.

In their current state, many commercial Bluetooth modules do not offer the full functionality of the specification.

4. Solutions

Some of the above mentioned limitations could be overcome. With Bluetooth Specification 2.0, a throughput of 10 mbps can be achieved. Also, for the interference problem, the frequency selection procedure can be modified to reduce the interference. The multiple piconets can coordinate among themselves to avoid this. The master of one piconet can get the set of frequencies used by the neighboring piconets and can select a non-overlapping sequence for its own piconet. There are some security issues involved with this solution but those can be resolved. Making the inquiring unit send its information in the inquiry request can solve the privacy problem involved in the inquiry procedure.

5. Viable Alternatives

Both the popular IEEE 802.11[40] for Wireless Local Area Networks (WLAN) and its competitor, HiperLAN/2[41], offer ad hoc modes for peer-to-peer communication. Because 802.11 requires a dedicated access point for many features such as QoS or power saving, its ad hoc mode is very limited. In HiperLAN/2, mobile terminals take over the role of access points while being in ad hoc mode and thus can continue to support QoS and power saving. Since these technologies are mainly intended for scenarios where mobile clients communicate through base stations, their transmission power is considerably higher than that of Bluetooth (10-300 mW, compared to 1 mW in Bluetooth). Future WLAN devices that support Transmit Power Control (TPC) might be a suitable alternative.

6. Conclusions

Originally intended as a cable-replacement technology, Bluetooth modules built fully to specification will be well suited for scenarios where a powerful master device (say a laptop) connects seamlessly to a number of peripherals (e.g., a printer, keyboard, or mouse). With data rates up to 1 Mbps, Bluetooth also offers more than enough bandwidth for simple sensor networks. However, scenarios involving a large number of identical low-power devices using ad hoc networking in a peer-to-peer fashion still face a number of obstacles when using Bluetooth as their communication technology.

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References

[1] P. Bonnet, A. Beaufour, M. B. Dydensborg, and M. Leopold, “Bluetooth-based sensor networks,” ACM SIGMOD Record, v.32 n.4, December 2003.

[2] A. Cerpa and D. Estrin, “ASCENT: adaptive self-configuring sensor network topologies,” In Proceedings of IEEE INFOCOM'02, June 2002.

[3] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, “Next century challenges: scalable coordination in sensor networks,” In Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking, p.263-270, August 15-19, 1999, Seattle, Washington, United States.

[4] D. Ganesan, B. Krishnamachari, A. Woo, D. Culler, D. Estrin, and S. Wicker, “Complex Behavior at Scale: An Experimental Study of Low-Power Wireless Sensor Networks,” In Technical Report UCLACSD-TR 02-0013,Computer Science Department, UCLA, July 2002.

[5] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, “System architecture directions for networked sensors,” In Proceedings of the ninth international conference on Architectural support for programming languages and operating systems, p.93-104, November 2000, Cambridge, Massachusetts, United States.

[6] M. Leopold, M. B. Dydensborg, and P. Bonnet, “Bluetooth and sensor networks: a reality check,” Proceedings of the first international conference on Embedded networked sensor systems, November 05-07, 2003, Los Angeles, California, USA

[7] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, “Wireless sensor networks for habitat monitoring,” In Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications, September 28-28, 2002, Atlanta, Georgia, USA

[8] G.J. Pottie, W.J. Kaiser “Wireless integrated network sensors,” Communications of the ACM vol. 43 (no. 5) pp 51-58, May 2000.

[9] K. Sohrabi, J. Gao, V. Ailawadhi, and G. Pottie, “A self-organizing sensor network,” In Proceedings of the 37th Allerton Conference on Communication, Control, and Computing (Monticello, Ill., Sept. 27-29), Dept. of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 1999.

[10] W. Feng and J. Walpole “Moving Towards Massively Scalable Video-Based Sensor Networks,” In Proceedings of Workshop on New Visions for Large-Scale Networks, Research and Applications, 2001.

[11] W. Feng, B. Code, E. Kaiser, M. Shea, and W. Feng, “Panoptes: scalable low-power video sensor networking

technologies," In Proceedings of the eleventh ACM international conference on Multimedia, November 02-08, 2003, Berkeley, CA, USA.
[12] Anonymous, "Bluetooth facts and fantasies," IBM. http://www.pc.ibm.com/europe/pcnews/bluetooth_facts_and_fantasies.html.
[13] Anonymous, "Bluetooth White Paper 1.1," AU-System, January 2000. http://whitepapers.zdnet.co.uk/0,39025945,60021120p-39000416q,00.htm.
[14] H. Bethoney, "Bluetooth Blues," ZDNet, Australia, November 2000. http://www.zdnet.com.au/news/business/0,39023166,20106791,00.htm
[15] Bluetooth SIG, "Beginners Guide to Bluetooth," 1999. http://www.blutooth.com.
[16] R. Bruno, M. Conti, and E. Gregori, "Bluetooth: Architecture, Protocols and Scheduling Algorithms," Cluster Computing, v.5 n.2, p.117-131, April 2002.
[17] M. Chillingworth, "Will Bluetooth Cut It?" ZDNet News, January 2001. http://www.zdnet.com.au/news/communications/0,2000061791,20150528,00.htm.
[18] K. Dawson, "Bluetooth Gets Real, Industry Standard," June 2000. http://www.technologyfront.com/journalism/2000/06/13.html.
[19] N. Deighton, "Bluetooth: the missing link in mobile E-commerce?" Research Note, Strategic Planning Assumption, Gartner Group, September 1999.
[20] S. Dennis, "Bluetooth Taking Off at Low End of Market," Newsbytes, London, Jan. 22, 2001. http://www.newsbytes.com/news/01/160814.html.
[21] R. Frazier, "Bluetooth a Boon for Wireless Devices," Cable News Network, April 20, 2000. http://sidebar.cnn.com/2000/TECH/computing/04/20/bluetooth.idg/index.html.
[22] M. Gerla, P.Johansson, R. Kapoor, and F. Vatalaro: "Bluetooth: last meter technology for nomadic wireless internetting," 12th Tyrhennian International Workshop on Digital Communications.
[23] J. Haartsen, "Bluetooth--the universal radio interface for ad-hoc wireless connectivity," Ericsson Review 3 (4) (1988) 1-5. available at http://www.ericsson.com/about/publications/review/1998_03/14.shtml.
[24] R. Mettala, "Bluetooth white Paper," Bluetooth SIG, Document No. 1 .C. 120/1.0, Aug. 1999. available at http://www.bluetooth.com.
[25] B.A. Miller, C. Bisdikian, and A. Edlund, "Bluetooth Revealed: the Insider's Guide to an Open Specification for Global Wireless Communications," Prentice-Hall, Englewood Cliffs, NJ, 2000.
[26] H. Monson, "Bluetooth Technology and Implications," Internet. Com, 2001. http://sysopt.earthweb.com/articles/bluetooth/index.html.
[27] N. J. Muller, "Bluetooth Demystified," McGraw-Hill Professional, 2000
[28] T. Müller, "Bluetooth Security Architecture," Bluetooth SIG Inc., United Kingdom, 07-15-1999, http://www.bluetooth.com/developer/download/download.asp?doc=174
[29] M. Nelson, "Bluetooth Interoperability Position Paper," Extended Systems, Boise, ID, February 2000. http://www.extendedsystems.com.
[30] A. Proust, "Personal Area Networks: a Bluetooth Primer," O'Reilly Network, November 2000. http://www.oreillynet.com/pub/a/wireless/2000/11/03/bluetooth.html.
[31] L. Quinn, "Bluetooth," Dell Technology Brief, Dell Corporate Communications, Austin Texas, US, August 1999. http://www.euro.dell.com/countries/ch/enu/gen/topics/vectors_1999-blue.htm.
[32] J. Quinn, "Bluetooth market study," Micrologic Research, Mic rologic Research Inc., Phoenix, Arizona, USA, 2001. available at http://www.mosmicro.com/Bluetooth. html.
[33] L. Rohde, "Analysis: Can Bluetooth Live Up to the Hype?" Cable News Network, July 12, 2000. http://sidebar.cnn.com/2000/TECH/computing/07/12/bluetooth.idg/index. html.
[34] K. Sand, "Bluetooth, Tik-111.550 Seminar on Multimedia," Telecommunications Software and Multimedia Laboratory, Helsinki University

of Technology, Helsinki University of Technology, Finland, March 1999. http://www.tml.hut.fi/Opinnot/Tik111.550/1999/Esitelmat/Bluetooth/bluetooth.html.
[35] D. Suvak, "IrDA and Bluetooth: a Complementary Comparison," Extended Systems, Boise, ID, 2000. http://www.extendedsystems.com.
[36] J. Wakefield, "Bluetooth: what is the potential?" Analysts Disagree, ZDNet UK News, April 1999. http://www.zd-net.co.uk/news/19-99/14/ns7758.html.
[37] S. Wolpin, "Bluetooth Arrives," January 2001. http://www.e-town.com/news/article.jhtml.
[38] B. S. Carlson, "A VLSI Circuit Design Course for Practitioners and Researchers," In MSE '97: Proceedings of the 1997International Conference on Microelectronics Systems Education (MSE '97), IEEE Computer Society, 1997.
[39] ITU-T Radio Regulations S5 – Frequency Allocations, 2001.
[40] IEEE 802.11 Working Group for Wireless Local Area Networks (WLANs) www.ieee802.org/11/
[41] ETSI HIPERLAN/2 Standard. http://portal.etsi.org/bran/kta/Hiperlan/hiperlan2.asp