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VARIABLE-BASE TACIT COMMUNICATION: A NEW ENERGY EFFICIENT COMMUNICATION SCHEME FOR SENSOR NETWORKS

by

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***Abstract*— Energy conservation is a major concern in wireless sensor networking. Conventionally in wireless communications, each bit transmitted by a node cost one unit of energy. Some recent advances, however, focus on silent time intervals between signal transmissions to convey information (Zhu and Sivakumar [1]). Such a scheme of Communication through Silence (CtS) introduces long delay while reducing energy consumption in sensor nodes. In this paper, we propose Variable-Base Tacit Communication (VarBaTaC) to mitigate the delay introduced by CtS. We also develop three MAC protocols based on VarBaTaC for different environments. We then outline experiment designs for further investigations and point out some interesting future research.**

I. Introduction

A wireless sensor network usually consists of a large collection of sensor nodes, and is often deployed in an open area with no wired or wireless networking infrastructure. Their applications include terrain monitoring, surveillance and discovery, environment control, and emergency pre-warning, ranging from military operations to civilian biological and geological/geographic information systems [2].

Being a complement to conventional communication networks, a sensor network has its unique features and hence challenges. In particular, the small sensor nodes are generally uni-purpose entities with limited capacities. Especially, they are constrained with energy as their batteries are not usually rechargeable.

Research efforts on reducing energy consumption of the sensor networks have spanned from reducing the payload of the network by intelligent data aggregation schemes [3], [4], to optimizing the data transmissions by selecting special paths or architectures [5], [6]. There are flourish efforts on MAC layer design [7] to accommodate special sensor requirements. Mhatre and Rosenberg [8] provides a good survey on cost and energy optimization methods for wireless sensor networks.

These efforts, however, are based on the conventional communication technique of sending information as binary strings of bits, called *Energy based Transmission* (EbT). A recent challenge work of Zhu and Sivakumar [1] proposes an alternative communication scheme in sensor networks, *Communication through Silence* (CtS). In CtS, instead of using a signal pulse to represent each bit, the communication can be performed by marking the start and the end of a period of time to convey information. For example, in order to transmit value 97 between, a 7-bit string $(1,1,0,0,0,0,1)$ is usually transmitted using EbT and thus 7 units of energy is consumed. In contrast, in CtS, such information can be conveyed by sending a start mark and an end mark with an silent period of 97 time slots, resulting in 2 units of energy consumption in total. CtS is innovative and can potentially result in significant energy saving, but it introduces undesirably long delay and is rather challenging in implementation. Issues left unsolved in Zhu and Sivakumar's CtS proposal include:

1) Throughput – CtS introduces long delay and thus affects the network throughput negatively. In particular, the loss in throughput is exponential to the gain in the energy. Although enhancements of CtS are discussed in Zhu and Sivakumar [1], these enhancements are not implementable without non-trivial treatments.
2) Sender identity – The inability of receivers' distinguishing the identities of message senders renders the throughput enhancements, e.g. multiplexing and fast-forwarding, impossible to implement.
3) Hidden terminals – When two senders transmit to the same receiver while they are not aware of each other, the transmissions collide at the receiver [9]. This classic problem may compromise the transmission reliability considerably in CtS.

In this paper, we propose variable-base tacit communication (VarBaTaC), a new energy efficient communication scheme for sensor networks. VarBaTaC generalizes both CtS and conventional binary coding based communications by using a variable coding base. For example, if a value 97 is to be transmitted and a base of 16 is chosen, it is first represented as $(6,1)$. The sender sends digit 6 and then digit 1 back to back using CtS for each digit. Compared to CtS, an extra pulse is inserted to separate these two digits. The delay introduced by CtS is thus controllable by the tuning the coding base and can be reduced significantly. (Compare the transmission time of 97 slots using CtS to that of $6+1$ using VarbaTaC.) In essence, both CtS and conventional EbT communication schemes are special cases of VarBaTaC with bases infinity and 2, respectively. Based on VarBaTaC, we address several practical concerns and propose three MAC layer protocols, i.e. a synchronous MAC, an asynchronous MAC, and an enhanced asynchronous MAC to overcome the hidden terminal problem.

The rest of this paper is organized as follows. In Section II, we review some related work. We present our new communication coding scheme VarBaTaC in Section III. Section IV describes three MAC schemes based on VarBaTaC. We conclude this paper and discuss some future research work in Section V.

II. Related Work

Sensor networks have enjoyed major research popularity in recent years due to their unique capabilities. A pioneering work addressing the challenges of sensor networks can be found in Estrin, Govindan, Heidemann and Kumar [10]. A general overview of area of wireless sensor networking is in Akyildiz, Su and Sankarasubramaniam [11]. Al-Karaki and Kamal [12] has recently surveyed the routing protocols used in sensor networking.

Gallager [13] studies basic limits on protocols' abilities in information transportation in data communication networks. Transmitting information in the form of binary strings of bits has been adopted as routine, Since in sensor networks, however, energy conservation plays a more critical role, Zhu and Sivakumar proposes CtS to trade throughput for energy. To mitigate the effect of long delay, they proposes three enhancement schemes.

- Multiplexing – Different senders can schedule different start and end time to "share" the bandwidth of the silent period. For example, if two senders, a and b, wish to send values 97 and 48, respectively. Node a can start at time slot 0 and end at 97 and node b can start at time slot 1 and end at time 49. Consequently, in 98 units of time, both nodes can transit their values in parallel.
- Cascading – When transmitting a strickly increasing sequence of data, e.g. $y_1, y_2, \ldots, y_m$, a sender transmits a start pulse at time 0, and then pulse at time y_i (for each $i = 1, 2, \ldots, m$). Thus, by making the receiver interprete the sequence of pulse incrementally, multiple values can be transferred in a period of y_m time slots.
- Fast forwarding – For multi-hop message relaying, an intermediate node can relay the message to the next hop without waiting for the end mark, thus to increase the transmission rate.

These enhancement proposals, however, are not viable without non-trival modifications to CtS. For example, in multiplexing, it is impossible for a receiver to distinguish the sender identity since discrete pulses (possibly from multiple senders) are the only information that it receives. In addition, these enhancements do not solve the intrinsic problem of long delay, where the delay is the information itself.

In our paper, we use a variable-base tacit communication (VarBaTaC) scheme to reduce transmission delay based on user requirements. We develop both contention-based and contention-free MAC protocols because VarBaTac should suitable to provide different support options to the upper layer. We address a series of practical problems in implementating VarBaTaC.

III. Variable-Base Tacit Communication

TABLE I
Table of notation

Notation	Meaning
M	length of message to be transmitted (bits)
b	frame coding base
d_i	value of the ith digit in coding
f	frequency that messages are generated at a node
l	number of digits in coding
$\mathbb{C}$	number of local node identities
cw	contention window size (slots)
x_i	random back-off value of node i
$SIPT$	short inter-pulse space

To control the delay in transmitting a message m whose numeric value is k, we code k with a base which can be tuned as needed. Here, k (equivalently m) can be transmitted as a sequence of "digits", each of which uses the CtS based transmission idea. Thus, by varying the value of the base, the delay in transmitting m can be controlled. In particular, value k ($0 \leq k \leq 2^M - 1$) to be transmitted is coded with a base b such that k can be represented by an l-digit number $d_{l-1}d_{l-2}\ldots d_1 d_0$, where $l = \left\lceil \frac{M}{\log b} \right\rceil$ and $0 \leq d_i < b$ ($i = 0, 1, 2, \ldots, l-1$). For example, when $M = 32$ and $b = 256$, m can be represented by $d_3 d_2 d_1 d_0$.

By introducing such a variable base b, we can ensure that the rate that a node transmits a message is at least the rate that the message is generated. That is, if the message is generated by a node at a frequency f messages per second, the node should be able to transmit at least fM data per second. To do that, we need to determine the maximum value of b. We assume that the PHY layer raw data rate is R (bits per second) Then the time needed to transmit a message using the base-b tacit communication scheme is $\frac{b \times \lceil \frac{M}{\log b} \rceil}{R}$. Consequently, the throughput constraint is

$$\frac{b \times \lceil \frac{M}{\log b} \rceil}{R} \leq \frac{1}{f}. \tag{1}$$

We can see that CtS is a special case when $b = 2^M$ and its throughput constraint is

$$\frac{2^M}{R} \leq \frac{1}{f} \Longrightarrow f \leq \frac{R}{2^M}, \tag{2}$$

which puts a heavy limit on the data reading frequency f allowed in the sensor nodes.

Notice that Equation 1 is a necessary condition to satisfy the throughput constraint since collisions between MAC frames can extra cause delay in transmission even if the data collected are infinitely compressible.

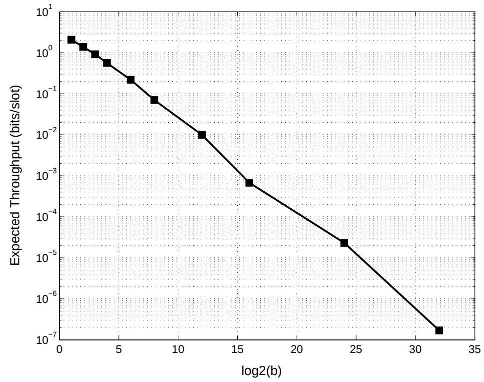

Fig. 1. Throughput vs. base.

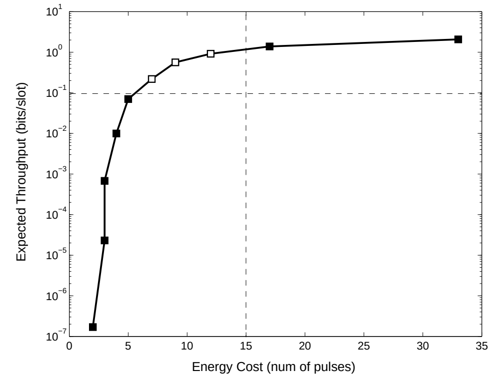

Fig. 3. Throughput vs. energy cost.

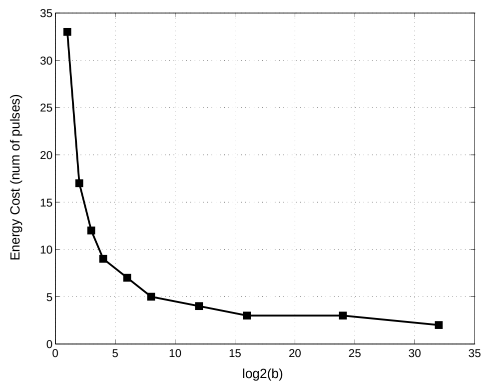

Fig. 2. Energy cost vs. base.

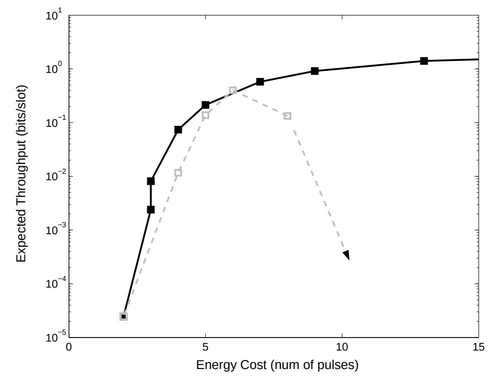

Fig. 4. Varied-base scheme vs. Original cascading with sorting.

As we can see, the ability in adjusting the base when forming MAC frames is especially appealing for sensor networks. In particular, when the network is used to aggregate data that are not infinitely compressible, the value of b should be set smaller when configuring nodes nearer to the sink. See Section V for more discussion on this.

To show the effects of base selection on throughput and energy cost, we calculate the average throughput and energy cost corresponding to the bases from 2^1 to 2^{32}, for messages of 32 bits, i.e. $M = 32$. Since pulses are added to separate digits, the energy cost for each frame is $l + 1$ times the energy for sending one pulse. The calculated values are listed in Table II and plotted as in the following figures.

TABLE II
EXPECTED THROUGHPUT AND ENERGY COST VS. BASE.

Base	Exp-throughput (bits/slot)	Energy cost (pulses)
2^1	2.0693414	33
2^2	1.3853289	17
2^3	0.9172492	12
2^4	0.5629582	9
2^6	0.2186344	7
2^8	0.0700227	5
2^{12}	0.0099580	4
2^{16}	0.0006770	3
2^{24}	0.00002310241	3
2^{32}	0.00000016956	2

As shown in Figure 1, the expected throughput declines exponentially with the exponential increase of the base, while Figure 2 shows that the energy cost to transmit each 32-bit frame for different bases is a reversely proportional function of $\log(b)$. Figure 3 is given to further illustrate the trade-off between throughput and energy consumption by selecting different bases. In reality, there can be varying applications and scenarios with different throughput requirements and energy constraints. As we mentioned earlier, with a fixed base, CtS makes available only one throughput option and may fail for applications that require higher throughput. By varying the base as shown in Figure 3, a variety of performance-cost combinations are provided to help us make decisions on adapting the base values for various application needs and physical condition limits. For example, suppose that an application requires a throughput of at least 0.1 bits/slot and that the energy consumption is at most 15 pulses per 32-bit frame as represented by a horizontal line and a vertical line in the figure. As a result, three points with b being 8, 16 and 64 marked with hollow squares can fulfill both requirements.

It is interesting to note that our variable-base method has some connection with the CtS cascading strategy of Zhu and Sivakumar [1]. In their work, a sequence of values ordered from the smallest to the largest can be transferred by sending a single start pulse, multiple intermediate pulses to separate those values, and a stop pulse. For each intermediate pulse, the receiver sensor continues counting instead of resetting the counter to zero until next pulse is received. The interval between the two pulses is the difference between the current value and the previous value, i.e. differentially coded. By such a cascading strategy, the delay is reduced. However, it can only be applied to increasingly ordered sequences. For sequences, one has to first sort the sequence and then to represent the side information of the order by some extra bits that are transmitted along with the ordered values. Compared to Zhu and Sivakumar's scheme, our variable-base method can be considered as another way of cascading while it avoids the overhead of transmitting the side information. In addition, for sensors with limited computing power, the cost of computation of our method, which is basically bit shifting, may be lower than the CtS cascading scheme based on sorting. At last, Figure 4 shows the throughput of both schemes. To plot the hollow squares on the curve representing CtS cascading plus sorting, we divide a 24-bit string into substrings of different lengths, sort the values of these substrings, and transmit the side order information along with the segment values back to back. Our variable-base method (indicated by the solid squares) outperforms CtS cascading with sorting (hollow squares) in terms of throughput for most of the cases.

IV. Medium Access Control

Here, we present three medium access control (MAC) protocols for VarBaTaC with increasing complexity. First, we assume that all communications are synchronized and a synchronous TDMA-based MAC is presented in Section IV-A. Second, we present an asynchronous MAC in which nodes contend for a common channel via CSMA/CA in Section IV-B. Furthermore, we address the hidden terminal problem by enhancing the previous MAC protocol with virtual carrier sensing capability (Section IV-C).

A. sVarBaTaC – Synchronous VarBaTaC

The synchronous MAC protocol of VarBaTaC, denoted *sVarBaTaC*, consists synchronized phases. Each phase has a period of $1/f$, where f is the data generation frequency (as in Section III). Each phase consists of $\mathbb{C}$ frames, where $\mathbb{C}$ is the number of local node identities used in the network. Here, the value of $\mathbb{C}$ can be obtained by executing a distributed distance-2 vertex coloring heuristic such that each vertex has an identity i between 0 and $\mathbb{C}-1$ and nodes with distance 2 must have different identities. During each frame i ($0 \leq i \leq \mathbb{C}-1$), a node with identity i (if there is any) transmits.

Each frame lasts for $\mathbb{C} + b \times l$ slots, where $l = \left\lceil \frac{M}{\log b} \right\rceil$, and consists of $l+2$ pulse. In particular, for sender s which has a frame intended to receiver r, slot 1 of the frame is a pulse indicating the start of the frame. Then after r slots comes the second pulse, which conveys the receiver's address. In the sequel, pulse j ($3 \leq j \leq l+2$) is transmitted after d_{l-j+2} slots of the previous pulse to convey the digit d_{l-j+2} of the base coded value of k. The remaining slots of the frame are idle until the next frame starts.

The sVarBaTaC is introduced more as a step-stone to convey the variable-base communication idea and thus may seem primitive. The drawbacks of the synchronous protocol include its low channel utilization and inflexible transmission scheduling. That is, it is possible that many frames out of the $\mathbb{C}$ frames of a phase are idle. Thus, not only can the channel be under utilized but also the delay in transmission may be large when considering the round-robin share among nodes. As we will see in the next section, these can be solved by using a smarter asynchronous MAC protocol.

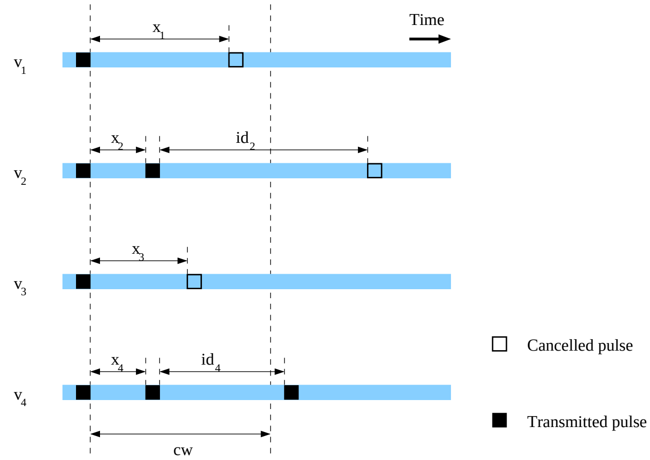

Fig. 6. Channel contention in aVarBaTac.

B. aVarBaTaC – Asynchronous MAC

In our asynchronous MAC, denoted *aVarBaTaC*, time is divided into slots and a node can attempt to transmit a frame at the beginning of any slot. In order for a node to start the transmission, it has to contend with all other nodes within its neighborhood and win the contention. Here, the entire frame consists of three stages, i.e. contention, tie breaking, and data.

In the contention stage, whenever a node s wants to send a frame to node r, it first listens to the channel. When its has been free for b slots, it chooses a random value x ($0 \leq x \leq cw-1$), where cw is the contention window. Then it waits for an additional x slots. The reason for waiting for at least b slots is an avoidance strategy to guarantee that node s does not interrupt any ongoing frame transmission. If it detects no pulse during this waiting period of $b+x$ slots, it transmits the first pulse and enters the tie-breaking stage. Then after s slots, it sends the second pulse, provided that the channel has been free since its first pulse. The purpose of this second pulse is two-fold. First, it is a tie breaker in case some other node s' also transmits the first pulse as s did, in which case, the node with larger ID quits the contention automatically. Second, it is also conveys the ID of the sender. After node s sends its second pulse, it is sure that it has won the channel contention and that it is the only node within its neighborhood that will continue to send the data part of the frame. Thus, node s enters the data transmission stage and, after a delay of r more slots, it transmits the third pulse to inform r of the data. In the sequel, pulse j ($4 \leq j \leq l+3$) is transmitted after d_{l-j+3} slots of the previous pulse to convey the digit d_{l-j+3} of the base coded value of k. Therefore, a frame consists of $l+4$ pulse and can last up to $(l+1) \times (b-1) + cw - 1$ slots.

Figure 6 illustrates a scenario where 4 neighboring nodes contend for the channel by starting to transmit the first pulse simultaneously. Then each node v_i ($i = 1, 2, 3, 4$) chooses a back-off value x_i to avoid collision. Suppose that $x_2 = x_4 <$

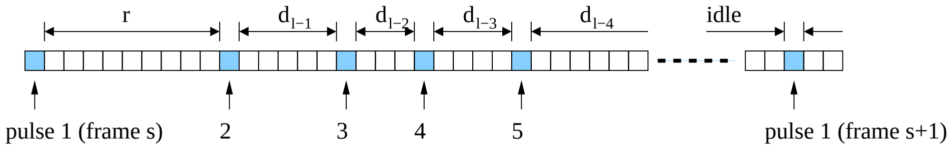

Fig. 5. Framing of sVarBaTaC.

$x_3 < x_1$. After x_2 time slots, nodes v_2 and v_4 each transmit a second pulse and, as a result, eliminate nodes v_1 and v_3. Again, suppose that v_4 has a smaller identity value id_4 than v_2 does. After id_4 slots, node v_4 transmits a third pulse and wins the channel contention.

Note that the tie breaking scheme stated as above can be biased to nodes with smaller ID's. That is, if multiple nodes choose the same back-off value x during the contention, the node with the smallest ID always wins the contention in tie breaking. However, as we can see later, the chance that such unfairness happens is small when we use a reasonable size of contention window.

The aVarBaTaC has two important and appealing properties.

- Complete resolution of contention – Since a tie breaking pulse is used, when there is a channel contention, exactly one contending node will win the contention. Thus, the efficiency of contention resolution is not compromised regardless of the load in the network.
- Unfairness is rare – As we can see in the following theorem, the probability that unfairness happens is small when cw is large compared to the number of contending nodes.

Theorem 4.1: Suppose that there are n nodes in a neighborhood that start to contend for the window at a particular moment. The probability that there is no collision, i.e. exactly one out of the n nodes chooses the smallest random back-off value, is at least $\left(\frac{cw-1}{cw}\right)^n$.

Proof. Let P_x denote the probability that exactly one node chooses the smallest back-off value x $(0 \le x \le cw-1)$ in a contention while the remaining $n-1$ nodes choose greater values. We have

$$P_x = \binom{n}{1} \times \left(\frac{1}{cw}\right) \times \left(\frac{cw-x-1}{cw}\right)^{n-1}$$

Summing over all values of $x = 0, 1, 2, \ldots, cw-1$, we have

$$\begin{aligned} & \sum_{x=0}^{cw-1} \binom{n}{1} \times \left(\frac{1}{cw}\right) \times \left(\frac{cw-x-1}{cw}\right)^{n-1} \\ = \quad & \frac{n}{cw^n} \times \left((cw-1)^{n-1} + (cw-2)^{n-1} + \ldots + 1^{n-1}\right) \\ \ge \quad & \frac{n}{cw^n} \times \frac{1}{n} \times (cw-1)^n \\ = \quad & \left(\frac{cw-1}{cw}\right)^n \end{aligned}$$

□

Thus, the probability that unfairness happens is usually small since the contention window size cw is usually set large compared to the number of nodes a neighborhood that may contend for the channel at a particular moment.

C. eVarBaTaC – Enhancement for hidden terminal resolution

The hidden terminal problem [9] is a classic problem in ad hoc networking and the MAC layer protocol has the responsibility to solve it. In our proposal, we can use a receiver's response to a frame addressed to itself in order to solve this problem. We call such an enhancement *eVarBaTaC*.

Here, we slightly modify the aVarBaTaC MAC option in Section IV-B to implement eVarBaTaC. To do that, we require that each sender, after transmitting a pulse, should pause for an extra small number of time slots before continuing with subsequence waiting and pulse transmission. Such an extra duration is called *short inter-pulse space* (SIPS), denoted $SIPT$, following the convention of MAC design in ad hoc and sensor networking. Typically, $SIPT$ can be as short as a single time slot. Remember that aVarBaTaC uses the 4th pulse to notify the receiver that the frame is addressed to this receiver. When the receiver realizes that there is a frame addressed to itself, it immediately transmits *two consecutive* pulses if it knows there is no ongoing transmission in its vicinity. Any node that overhears two consecutive pulses must defer any frame transmission by at least $l \times (b + SIPT)$ slots before it contends for the medium. That is, the medium within the the vicinity of the receiver is reserved for $l \times (b + SIPT)$ time slots. In this case, the sender waits for $b_{l-1} + SIPT + 1$ slots and transits the pulse, which marks the end of the first d_{l-1}. If, however, the sender does not hear two consecutive pulses after transmitting the 4th pulse, possibly because the receiver is deferring to other ongoing transmission, the sender cancels sending the rest of the frame and contend again for the medium to re-send the frame later.

The scenario in Figure 7 depicts an example where the receiver r has successfully reserved the medium.

V. Conclusion and Future Work

This paper proposed the use of time to convey information in wireless sensor networks in order to conserve energy of the sensor nodes, called VarBaTaC. VarBaTaC uses a variable coding base to control the trade-off between network throughput and energy saving. To implement VarBaTaC, we presented three MAC protocols to meet different application needs. The MAC protocols are sVarBaTaC, the synchronous MAC, aVarBaTaC, the asynchronous MAC, and eVarBaTaC, the enhancement to address the hidden terminal problem.

It will be interesting to test VarBaTaC and the above MAC options to see the interplay between energy saving and network throughput. Since frames can be lost due to various adversarial factors in an energy-constrained wireless sensor network, we plan to test the actual network throughput under different network load settings and different MAC implementations. In

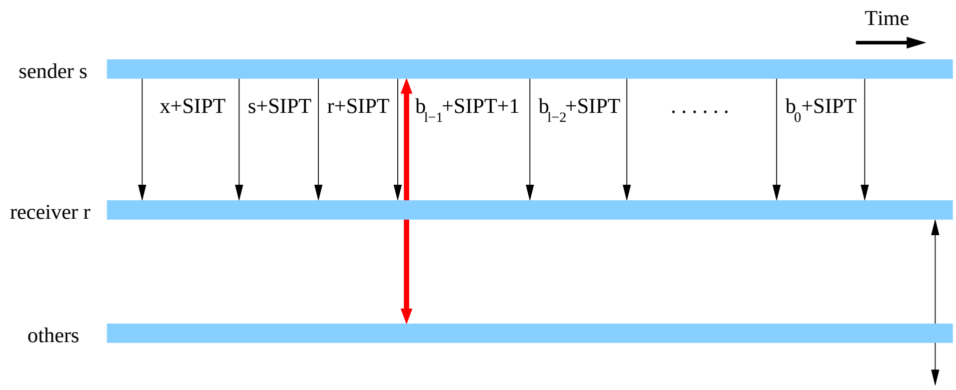

Fig. 7. Hidden terminal resolution.

particular, aVarBaTaC provides higher scalability than sVarBaTaC by introducing contention. Tests will be done to find out how much throughput gain aVarBaTaC introduces while how much energy is consumed by contention resolution. The hidden terminal enhancement, eVarBaTaC, reduces frame collisions by adding virtual carrier sense. How much throughput gain is obtained using eVarBaTaC? How much does it help to save energy by increasing the probability of successful frame transmission? How fair is the tie-breaking scheme? These are also something that we plan to find out from experiments.

Further extensions that are intriguing but beyond the scope of this paper include

- Depending on the measurements taken by the network, the data rates at different locations of the network may vary due to data fusion. Thus, it will be helpful to determine the transmission base b of each node as needed. Since these bases are usually determined at network initialization, it will be an interesting design problem.
- It is possible to dispense with the sender ID when transmitting a frame. To do that, the transmission time or order within a neighborhood can be used to identify the sender. Therefore, we can organize the transmissions of the nodes, say, to accomplish a "convergecast"[1], in compliance with the restriction of wireless medium sharing. This resembles the classic broadcasting problem in wired networks, as surveyed by Hedetniemi, Hedetniemi and Liestman [14].

References

[1] Y. Zhu and R. Sivakumar, "Challenges: Communication through silence in wireless sensor networks," in *Proceedings of The Eleventh Annual International Conference on Mobile Computing and Networking (MOBICOM)*, Cologne, Germany, September 2005, pp. 140–147.

[2] F. Zhao and L. Guibas, *Wireless Sensor Networks : An Information Processing Approach (Morgan Kaufmann Series in Networking)*. Morgan Kaufmann, 2004.

[3] Y. P. Chen, A. L. Liestman, and J. Liu, "Energy-efficient data aggregation hierarchy for wireless sensor networks," in *Second International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine'05)*, Orlando, Florida, August 2005.

[4] S. Madden, R. Szewczyk, M. J. Franklin, and D. E. Culler, "Supporting aggregate queries over ad-hoc wireless sensor networks," in *Proceedings of the 4th IEEE Workshop on Mobile Computing Systems and Applications (WMCSA)*, Callicoon, NY, June 2002, pp. 49–58.

[5] W. B. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proceedings of the 33rd International Conference on System Sciences (HICSS)*, Hawaii, January 2000.

[6] C. Intanagonwiwat, R. Govindan, D. Estrin, J. S. Heidemann, and F. Silva, "Directed diffusion for wireless sensor networking," *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 2–16, February 2003.

[7] I. Demirkol, C. Ersoy, and F. Alagoz, "Mac protocols for wireless sensor networks: a survey," *To appear in IEEE Communications Magazine*, 2005.

[8] V. Mhatre and C. Rosenberg, "Energy and cost optimizations in wireless sensor networks: A survey," in *Performance Evaluation and Planning Methods for the Next Generation Internet (25th Anniversary Volumes of GERAD)*, A. Girard, B. Sanso, and F. Vazquez-Abad, Eds. Kluwer Academic Publishers, 2005.

[9] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part ii – the hidden terminal problem in carrier sense multiple-access modes and the busy-tone solution," *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1417–1433, 1975.

[10] D. Estrin, R. Govindan, J. S. Heidemann, and S. Kumar, "Next century challenges: Scalable coordination in sensor networks," in *Proceedings of The Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM)*, Seattle, WA, 199o, pp. 263–270.

[11] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, March 2002.

[12] J. N. Al-Karaki and A. E. Kamal, "Routing techniques inwireless sensor networks: A survey," *IEEE Wireless Communications*, vol. 11, no. 6, p. 6C8, December 2004.

[13] P. Gupta and P. R. Kumar, "Basic limits on protocol information in data communication networks," *IEEE Transactions on Information Theory*, vol. 22, no. 4, pp. 385–398, July 1976.

[14] S. M. Hedetniemi, S. T. Hedetniemi, and A. L. Liestman, "A survey of gossiping and broadcasting in communication networks," *Networks*, vol. 18, pp. 319–349, 1988.

[1]A convergecast refers to the operation that each node of the network has a message to send to a single destination.