

## References

- 1 MARSHALL, I., and ROADKNIGHT, C.: 'Linking cache performance to user behaviour', *Comput. Netw. ISDN Syst.*, 1998, 30, (22-23), pp. 2123-2130
- 2 TAQQU, M.S., WILLINGER, W., and SHERMAN, R.: 'Proof of a fundamental result in self-similar traffic modelling', *Comp. Commun. Rev.*, 1997, 27, (2), pp. 5-23
- 3 PAXSON, V.: 'Fast, approximate synthesis of fractional gaussian noise for generating self-similar network traffic', *Comput. Commun. Rev.*, 1997, 27, (5), pp. 5-18
- 4 FAN, Z., and MARS, P.: 'Self-similar traffic generation and parameters estimation using wavelet transform'. GLOBECOM 97, IEEE Global Telecommunications Conf., 1997, Vol. 3, pp. 1419-1423
- 5 ERRAMILI, A., SINGH, R.P., and PRUTHI, P.: 'Chaotic maps as models of packet traffic'. Proc. ITC14, The Fundamental Role of Teletraffic in the Evolution of Telecommunication Networks, 1994, pp. 329-338
- 6 SAMUEL, L.G., PITTS, J.M., and MONDRAGON, R.J.: 'Towards the control of communication networks by chaotic maps: Source aggregation' in RAMASWAMI, V., and WIRTH, P.E. (Eds.): 'Proc. ITC15, Teletraffic Contributions for the information age' (Elsevier, Amsterdam, 1997), Vol. 2b, pp. 1369-1378
- 7 SAMUEL, L.: 'The application of non-linear dynamics to teltraffic modelling'. PhD Thesis, University of London, 1999
- 8 MONDRAGON, R.: 'A model of packet traffic using a random walk model', *Int J. Bifurc. Chaos*, 1999, 9, (7), pp. 1381-1392

## Collaborative network of wireless micro-sensors

S. Arnon

One of the new features of telecommunication systems is wireless micro-sensor networks. Remote communication using a specific sensor is impossible due to the limited transmitter power and antenna gain of the sensor. In this work, the authors propose a remote communication model using a collaboration procedure between the sensors.

**Introduction:** New technologies such as microelectronic mechanical systems (MEMS), communication systems on chips and new algorithms are set to revolutionise the technology and availability of sensing information in all fields of life (medical, environmental quality, domestic, etc.). One of the first products of this revolution has been smart dust [1]. Smart dust is an on-chip micro-sensor with communication capability. Several micro-sensors are allocated per sensing location. The main limitations of micro-sensors are their limited transmitter power and antenna gain. Remote communication (outside the sensor network) is impossible due to these limitations. In this Letter, we present a collaborative model in which the resources of several sensors are combined to make remote communication to a specific sensor possible. In this case, the collaboration was effected by information exchange using the inter-network links (the links between the sensors). All the collaborating sensors transmit the information based on the information received from the source sensor. Collaboration between the sensors is essential in order to achieve high performance communication with the limited resources (power, antenna gain, bit rate and bit error rate) per sensor. Our research deals first with the protocol for establishing the collaboration and secondly with the optimum method for combining the signals received.

**Communication protocol:** The scenario under consideration comprises a network of sensors and a master unit (Fig. 1). The remote measurement starts with a command from the master unit to a specific sensor to carry out measurements and transmit the information. The master unit's high-power transmitter enables long-range communication. This command begins the initialisation procedure for establishing the collaboration. The selected sensor broadcasts a 'request for collaboration' command. Based on responses from the collaborating sensors, the selected sensor calculates first the number of collaborating sensors and secondly the bit error rate (BER) of collaborating sensors' links. The selected sen-

sor transmits this information. The collaborating sensors receive the information, make a decision and then transmit the decision. Each sensor transmits using a different code (allocated code; CDMA system). The master unit receives the signals and extracts the information. It may take several repetitions in order to receive the message without error and extract the weight coefficient for each branch (link from the selected sensor to the collaborating sensor and from the collaborating sensor to the master unit). The procedure for receiving the weight coefficient is carried out only once for static sensors and for every access to mobile sensors. This step ends the initialisation procedure. From this point on, the selected sensor transmits the information to the master unit.

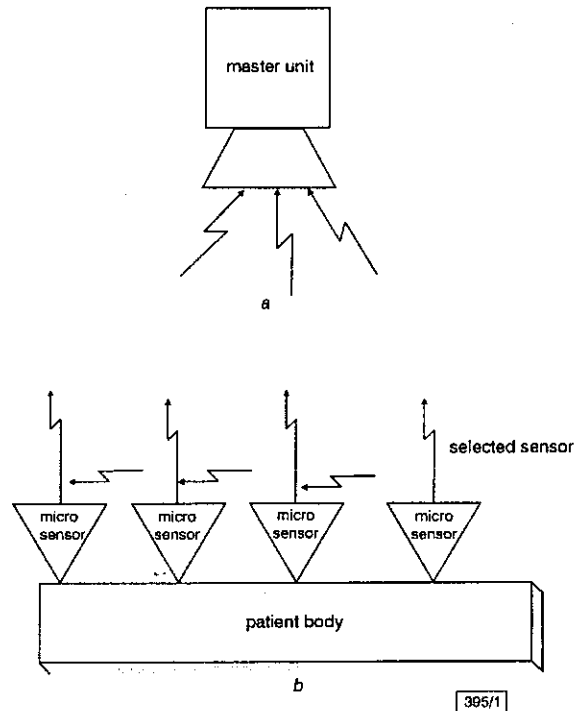


Fig. 1 Wireless micro-sensors network and master unit

a Master unit  
b Wireless sensors network

**Optimum combination of information:** This Section describes how to combine the information from the sensors in an optimum manner. The sensor includes a receiver, a transmitter and a sensing/measuring unit. A specific code (CDMA system) is allocated to each sensor. The sensor receivers can receive all the other sensor signals. The optimisation procedure uses the maximum likelihood decision rule. The global decision rule is based on the information from the sensors and the branch performance (BER). In our formulation '−1' or '1' represent decision '0' or '1'.

The maximum global likelihood (ML) decision rule is [2]

$$\prod_{i=1}^L \frac{P(d_i|1)}{P(d_i|-1)} > 1 \quad (1)$$

where  $P(d_i|1)$  is the ratio between the correct decision to wrong decision probability of branch  $i$  when transmitting '1',  $P(d_i|0)$  is the ratio between the correct decision to wrong decision probability of branch  $i$  when transmitting '−1', and  $d_i$  is the local decision.

The probability ratio for transmitting '1' is

$$P(d_i|1) = \left( \frac{1 - P_i}{P_i} \right)^{\frac{1+d_i}{2}} \quad (2)$$

where

$$P_i = P_i(1)(1 - P_i(2)) + (1 - P_i(1))P_i(2) \quad (3)$$

The probability ratio for transmitting '−1' is

$$P(d_i|-1) = \left( \frac{P_i}{1 - P_i} \right)^{\frac{1-d_i}{2}} \quad (4)$$

The selected sensor (defined by index 1) to the sensor  $i$  link error probability is given by

$$P_i(1) = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{G_s^2 P_s \left(\frac{c}{4\pi f r_{i,i}}\right)^2}{B \left( N_{0s} + \frac{1}{W} \sum_{j=2 \neq i}^L G_s^2 P_s \left(\frac{c}{4\pi f r_{i,j}}\right)^2 \right)}} \right) \quad i \neq 1 \quad (5)$$

$$P_1(1) = 0 \quad (6)$$

The numerator term represents the signal. The first term in the denominator is the thermal noise, the second term is the multi-user interference,  $G_s$  is the sensor antenna gain,  $P_s$  is the sensor power transmitter,  $f$  is the communication frequency,  $r_{i,j}$  is the distance between sensor  $i$  and sensor  $j$ ,  $c$  is the speed of light,  $N_{0s}$  is the thermal noise density power,  $B$  is the data rate,  $W$  is the CDMA spreading bandwidth, and  $\operatorname{erfc}(x)$  is the complementary error function.

The sensor  $i$  to master unit link error probability is given by

$$P_i(2) = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{G_s G_M P_s \left(\frac{c}{4\pi f R_i}\right)^2}{N_{0M} B}} \right) \quad (7)$$

where  $R_i$  is the distance between sensor  $i$  and the master unit,  $N_{0M}$  is the thermal noise density power and  $G_M$  is the master unit receiver antenna gain. We assume that the master unit cancels multi-user interference, so that in eqn. 7 the multi-user interference is not included.

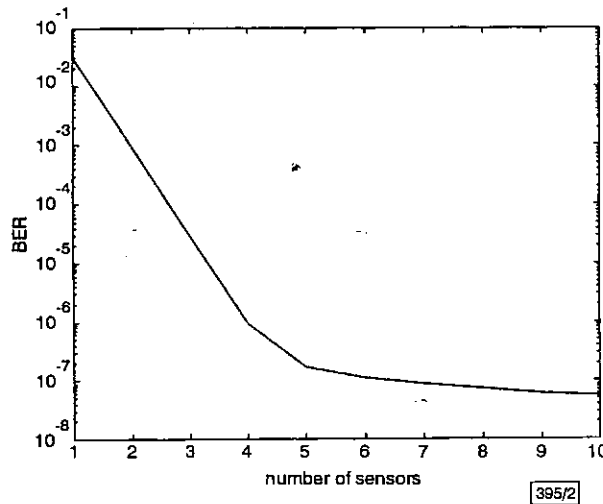


Fig. 2 BER against number of collaborating sensors

Taking the logarithm of eqn. 1 yields

$$X = \sum_{i=1}^L d_i \ln \left( \frac{1 - P_i}{P_i} \right) > 0 \quad (8)$$

The error probability (assuming '1' is transmitted) is

$$BER = P(X < 0) = \int_{-\infty}^0 f_X(X) dX \quad (9)$$

The probability density function (PDF) of the sum is the  $L$ -fold convolution of the partial PDF. In most cases, the calculation of this function is very complicated. A Chernoff upper-bound makes it possible to obtain a simpler expression such as

$$BER < E \left\{ \exp \left( -t^* \sum_{i=1}^L x_i \right) \right\} \quad (10)$$

The tightest upper-bound is created for  $t = 0.5$  (easy to prove). So from eqn. 10 we can conclude that the BER is upper bounded by

$$BER < 2^L \prod_{i=1}^L \left( \sqrt{P_i(1 - P_i)} \right) \quad (11)$$

*Example:* Consider a hospital patient monitored by ten wireless micro-sensors (Fig. 1). The remote master unit interrogates the sensors. In this example, we show the communication system performance improvement as a function of the number of collaborating sensors. The sensors are placed on the patient's body. The sensors are 0.18m apart. The master unit is placed on the ceiling of the room. The distance between the master unit and the selected sensor is 30m. The sensor antenna gain is  $-13$ dB, the thermal noise is  $-198$ dB, and the transmitter power is  $-35$ dBm. The master unit antenna gain is 3dB and the thermal noise is  $-204$ dB. The communication frequency is 5GHz. The data rate is 30kbit/s and the spreading bandwidth is 3MHz.

Fig. 2 shows the BER as a function of the number of collaborating sensors. It can be seen that increasing the number of collaborating sensors from 1 to 10 decreases the BER dramatically from  $2 \times 10^{-2}$  to  $5 \times 10^{-8}$ . The improvement in the BER is slight for more than five collaborating sensors due to the fact that the additional sensors create added interference, but on the other hand the branch performance is low (remote from the selected sensor).

*Summary and conclusions:* In this Letter, we have proposed the use of collaborating sensors in order to make long-range communication possible. Future work will consider using collaborative methods such as the use of multi-receivers to overcome fading or to obtain faster code synchronisation using network information.

*Acknowledgment:* The author is grateful for the support of the Fulbright fund.

© IEE 2000

10 November 1999

Electronics Letters Online No: 20000181

DOI: 10.1049/el:20000181

S. Arnon (Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA)

E-mail: shlomi@lids.mit.edu

## References

- KAHN, M., KATZ, R.H., and PISTER, K.S.J.: 'Mobile networking for smart dust'. ACM/IEEE Int. Conf. Mobile Computing and Networking (MobiCom 99), Seattle, WA, 17-19 August 1999
- CHAU, Y.A., and SUN, J.T.: 'Diversity with distributed decisions combining for direct-sequence CDMA in a shadowed Rician-fading land mobile satellite channel', *IEEE Trans. Veh. Tech.*, 1996, 45, (2), pp. 237-247

## Effect of signal quantisation on WCDMA code acquisition

J. Iinatti and K. Hooli

The effect of signal quantisation on noncoherent matched filter code acquisition in a direct-sequence code division multiple access (CDMA) system is considered. The signal structure is applicable to a wideband CDMA system. The effect of quantisation is derived mathematically and verified using computer simulations with several users. The results indicate that the effect of quantisation is not significant, i.e. from the point of view of acquisition, only a few bits are needed. The effect of signal quantisation can be modelled as a noise increase.

*Introduction:* Code synchronisation is one of the key tasks in every spread spectrum (SS) receiver. It is performed in two steps: initial synchronisation, i.e. acquisition, and fine synchronisation, i.e. tracking. In the passive correlation method, a filter matched to the spreading code is used. Acquisition is usually performed using a noncoherent receiver because the carrier phase estimation is very difficult from the received wideband signal with low signal-to-noise ratio. The effect of signal quantisation from the point of view of data detection has been considered extensively, for example in [1]. In [2], saturation effects on coherent code acquisition due to quantisation have been considered when multiaccess inter-