A Comparative Study of Wireless Communication Network Configurations for Medical Applications

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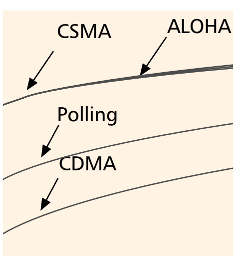

The potential of using wireless sensors with communication capacities, operating in the radio frequency range, would alleviate problems for the patient and for the medical staff, and increase the efficiency of the hospital's performance by increasing patient throughput.

Abstract

A comparative study of the performance characteristics of five multiple access configurations for a wireless communication network is presented and evaluated within the context of the medical field of application. A universal variable has been defined for comparison between the alternative configurations, embodying the data rate, number of channels, power consumption, and bandwidth requirements. Special medical specifications have been accommodated, while the broader applications of this approach have been addressed. CDMA is indicated as the preferred method, over ALOHA, slotted ALOHA, CSMA, and polling.

Introduction

A familiar scenario in hospital treatment of patients, in emergency and outpatient as well as long- and short-term hospitalization, is characterized by connecting the patient to instrumentation that measures and records vital signals. This is labor-intensive for the medical staff, and often unpleasant and restricting for the patient. The potential of using wireless sensors with communication capacities, operating in the radio frequency range, would alleviate the problems of the above described scenario, for both the patient and medical staff, and increase the efficiency of the hospital's performance by increasing patient throughput. Hopefully, hospitalization could be abbreviated, while some degree of medical supervision could nevertheless be maintained.

From a wireless communication viewpoint the specific problems presented by the proposed field of application derive from the nature of the signals, which are of widely differing power levels and data rates, and the hospital environment. An individual patient may be the source of a number of recorded medical signals, while similar signals may be received from a number of different patients simultaneously. Since human life and health are the issue, a high level of accuracy and reliability are essential. The closed space of hospital examination rooms and the presence of all manner of medical instrumentation pose additional problems to successful wireless communication due to multipath interference and mutual disturbances between transmissions.

Low power requirements are necessary both from safety considerations and because in mobile communications the battery lifetime must be commensurate with the application, often several hours.

The problems outlined above are addressed in defining the signal parameters and restraints. Electrocardiogram (ECG), heart rate, heart sound, electro-encephalogram (EEG), electromyogram (EMG), respiratory rate, and body temperature have been selected as the signals to be monitored.

The five access control regimes — ALOHA, slotted ALOHA, carrier sense multiple access (CSMA), polling, and code-division multiple access (CDMA) — are outlined and characterized. Minimum, maximum, and total power requirements are of interest, as well as average power.

Overall minimum power requirements are sought, while bandwidth is maximized within the dictates of necessary and desired data rates. Universal performance parameters are derived to enable comparison of the different multiple access solutions, and several scenarios are investigated with the help of mathematical models and computer simulations.

Mobile wireless communication is familiar in cellular telephones and paging, but the proposed idea breaks new ground in system complexity, and the analytic tools developed are unprecedented. While the unique aspects of the medical environment are modeled here, the application potential of the analytical tools developed extends to other arenas.

Following a brief presentation of the medical data and multiple access configurations, we unfold the analytical approach to system evaluation and expand on the comparative appraisal. Finally, suggestions are made for further work and areas of application.

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Biomedical measurements	Voltage range (V)	Number of users = K (sensors)	Bandwidth (Hz)	Sample rate (samples/s) = (Hz)	Resolution [b/sample]	Information rate [b/s]
ECG	0.5–4 m	5–9	0.01–250	1250	12	15,000
Heart sound	Extremely small	2–4	5–2000	10,000	12	120,000
Heart rate	0.5–4 m	2	0.4–5	25	24	600
EEG	2–200 µ	20	0.5–70	350	12	4200
EMG	0.1–5 m	2+	0–10,000	50,000	12	600,000
Respiratory rate	Small	1	0.1–10	50	16	800
Temperature of body	0–100 m	1+	0–1	5	16	80

Bandwidth = $f_{max} - f_{min}$
Sample rate = 5_f_{max}
Information rate = R_b = Resolution_Sample rate

Table 1. *Biomedical measurements.*

The Medical Signals

As mentioned in the introduction, seven vital signals are to be monitored in our model. Each provides different and complementary information on the well being of the subject, and for each specific examinee the anticipated range of signal parameters is different [1–5]. For example, heart rate may vary between 25 and 300 beats/min for normal people in different circumstances; likewise, breathing rate could be between 5 and 50 breaths/min. EEG, ECG, and EMG are considerably more complex signals with spectra spanning up to 10 kHz. Voltage levels of the recorded signals vary from less than 1 µV to tens of millivolts. Not all the signals are required for each examinee. The pertinent data is summed up in Table 1.

The Multiple Access Configurations

The five multiple access configurations under investigation can be further subdivided into random access systems — ALOHA, slotted ALOHA, and CSMA — and polling and CDMA, which are conceptually different [6–15].

Random Access Systems

In random access systems, the prime concern in achieving a viable system is to minimize collisions of packets of digital information that may be sent simultaneously from different users, while maintaining adequate flow of information.

Assuming K users transmit over the total W bandwidth of the channel, sending packets of duration T_p at a rate of $1/NT_p$, the average rate at which packets enter the network is given by

$$\lambda = K/NT_p \text{ packets/s.} \quad (1)$$

Furthermore, assuming randomness of transmissions (each user is independent), we use the Poisson distribution to describe the probability that m packets will enter the network during time interval τ:

$$P(m,\tau) = \frac{e^{-\lambda\tau}(\lambda\tau)^m}{m!}. \quad (2)$$

In the case of ALOHA [10, 11], a rival message initiated within ($\pm$) T_p of the start time of a packet of information will cause a collision. Thus, the probability of a free channel is given by

$$P_0 = P(0,2T_p) = e^{-2K/N}. \quad (3)$$

The throughput of the system, S, defined as the number of packets successfully received per second, is given by

$$\begin{aligned} S &= (K/NT_p)P_0 = (K/NT_p)e^{-2K/N} \\ &= \rho/T_p e^{-2\rho}, \end{aligned} \quad (4)$$

where $\rho = K/N$ represents the input density to the network.

S is maximized when

$$\rho = K/N = 1/2, \quad (5)$$

$$S_{max} = (1/2T_p)e^{-1}. \quad (6)$$

In slotted ALOHA [10, 11], time is predivided into slots of duration T_p; the user indicates his/her intention to transmit during one slot and transmits at the beginning of the next slot. Thus, collisions only occur if more than one user wish to transmit during the duration of the same time slot T_p, so Eqs. 3, 4, 5, and 6 become

$$P_0 = P(0, T_p) = e^{-K/N} = e^{-\rho}, \quad (7)$$

$$S = (K/NT_p)\, P_0 = (\rho/T_p)e^{-\rho}. \quad (8)$$

At maximum throughput:

$$\rho = K/N = 1, \quad (9)$$

$$S_{max} = (1/T_p)e^{-1}. \quad (10)$$

This is twice the throughput of regular ALOHA, but transmission time is restricted to distinct points in time, resulting in a potential increase in "dead time," when the channel is not in use.

In the third random access system under study, CSMA, each user "listens" to the channel to ensure that no other user is transmitting before sending its package [6]. The latency between transmission by user one and the perception of user two is the source of collisions and defined as T_d. Hence, the probability of a collision is given by

> Bearing in mind the dictates of the medical environment mentioned, we may sum up the communication system criteria for comparative study of multiple access configurations as minimum power and maximum bandwidth efficiency.

$$P_{collision} = 1 - P(0,T_d) = 1 - e^{-\rho T_d/T_p}. \quad (11)$$

The probability of no collision, P_{nc}, is given by

$$P_{nc} = e^{-\rho T_d/T_p}. \quad (12)$$

The throughput of CSMA can be shown to be described by

$$S_{CSMA} = \frac{1}{T_p}\left(\frac{\rho}{\rho+1}\right)e^{-\rho T_d/T_p}. \quad (13)$$

If the propagation delay is not high, CSMA yields a higher throughput than either of the ALOHA configurations.

Other Access Systems

Polling is an access system built on a different concept than the above described random access systems. Each user is applied to by the base station and invited to transmit any awaiting data up to a predefined number of packages. This eliminates collisions and excessive dead time, but can be inefficient if many users are invited to transmit when they have no data to send, while others wait in line while their heavy baggage of packages requires several transmission slots. Knowledge of the system enables priority polling, giving preference to heavier users, but time is necessarily expended polling redundant users and addressing each transmission to identify the sender.

In CDMA, the narrowband signal is muffled by being multiplied by a broadband spread spectrum pseudo noise (PN) signal [8, 9–13]. Near orthogonality of the PN code facilitates decoding at the receiver, and a large number of independent signals can be transmitted simul- taneously with success. Power control is necessary to prevent the stronger (often briefer transmission distance) signals obscuring the weaker signals, since the noise level is signal-power-related.

Recalling the general theoretical communications capacity relation (Shannon's channel capacity formula),

$$C = W\log\left(1+\frac{P}{\hat{N}}\right), \quad (14)$$

C = channel capacity (bits per second),

$P/\hat{N}$ = signal-to noise-ratio (SNR),

we deduce that the very large bandwidth of CDMA mitigates the problem of interference while maintaining high data rates.

The Communication Criteria

Bearing in mind the dictates of the medical environment mentioned in the introduction, we may sum up the communication system criteria for comparative study of multiple access configurations as minimum power and maximum bandwidth efficiency.

At the hardware level, analog-to-digital (A/D) and digital-to-analog (D/A) converters interface between the signal generation (sensor on the human body), transmission (digital), and data processing stages. To normalize bandwidth requirements, and thus optimize bandwidth efficiency, a uniform bit rate can be achieved by adjusting the A/D and D/A clock and resolution (bits/sample) parameters. The sample rate is determined by the maximum frequency of the signal and the clock rate.

The average power, $\overline{P}$, received from all K_i users can be summed up as

$$\overline{P} = \frac{\sum_{i=1}^{M} K_i P_i(R_{bi},K_i)}{\sum_{i=1}^{M} K_i}, \quad (15)$$

M = number of different measurements,

$P_i\,(R_{bi}, K_i)$ = average power received from a single user at the uniform rate R_{bi}.

The Mathematical Models

Random Access Systems

Adding the following definition of $\hat{N}$ to the expressions stated and derived in Eqs. 1–15, we proceed to list the channel capacity and average power for each of the three random access systems,

$$\hat{N} = (K-1)\,P + N_0W, \quad (16)$$

where N_0 = thermal noise spectral density.

For the ALOHA system we derive the following expressions [10]:

$$C_{ALOHA} = \rho\exp(-2\rho)W\ln\left(1+\frac{P}{\rho[(K-1)P+N_0W]}\right) \quad (17)$$

$$P_{ALOHA} = \frac{\left(2^{\left(\frac{C}{\rho W\exp(-2\rho)}\right)}-1\right)\rho N_0 W}{1-\left[\left(2^{\left(\frac{C}{\rho W\exp(-2\rho)}\right)}-1\right)\rho(K-1)\right]} \quad (18)$$

Using Eq. 15, we find that the average total power for K users is given by

$$\overline{P}_{ALOHA} = \frac{1}{K}\sum_{i=1}^{M} \frac{\left(2^{\frac{1}{K_i\exp\left(\frac{-2K_iR_{bi}}{W}\right)}}-1\right)-1K_i^2R_{bi}N_0}{1-\left[\left(2^{\frac{1}{K_i\exp\left(\frac{-2K_iR_{bi}}{W}\right)}}-1\right)\frac{K_iR_{bi}}{W}(K_i-1)\right]} \quad (19)$$

For slotted ALOHA, replacing 2ρ by ρ, the equivalent expressions are given by

$$C_{Slotted\_ALOHA} = \rho\exp(-\rho)W\ln\left(1+\frac{P}{\rho[(K-1)P+N_0W]}\right) \quad (20)$$

$$P_{Slotted\_ALOHA} = \frac{\left(2^{\left(\frac{C}{\rho W \exp(-\rho)}\right)} - 1\right)\rho N_0 W}{1 - \left[\left(2^{\left(\frac{C}{\rho W \exp(-\rho)}\right)} - 1\right)\rho(K-1)\right]} \quad (21)$$

$$\bar{P}_{Slotted\_ALOHA} = \frac{1}{K}\sum_{i=1}^{M} \frac{\left(2^{\frac{1}{K_i \exp\left(\frac{-K_i R_{bi}}{W}\right)}} - 1\right) K_i^2 R_{bi} N_0}{1 - \left[\left(2^{\frac{1}{K_i \exp\left(\frac{-K_i R_{bi}}{W}\right)}} - 1\right)\frac{K_i R_{bi}}{W}(K_i - 1)\right]} \quad (22)$$

In the case of CSMA, substituting for maximal throughput, we get [6]

$$C_{CSMA} = \frac{\rho}{1+\rho}\exp(-2\rho) W \ln \left(\frac{P}{\rho[(K-1)P + N_0 W]}\right) \quad (23)$$

$$P_{CSMA} = \frac{\left(2^{\left(\frac{C(1+\rho)}{\rho W \exp(-2\rho)}\right)} - 1\right)\rho N_0 W}{1 - \left[\left(2^{\left(\frac{C(1+\rho)}{\rho W \exp(-2\rho)}\right)} - 1\right)\right]\rho(K-1)} \quad (24)$$

$$\bar{P}_{CSMA} = \frac{1}{K}\sum_{i=1}^{M} \frac{\left(2^{\frac{1+\frac{K_i R_{bi}}{W}}{K_i \exp\left(-2\frac{K_i R_{bi}}{W}\right)}} - 1\right) K_i^2 R_{bi} N_0}{1 - \left[\left(2^{\frac{1+\frac{K_i R_{bi}}{W}}{K_i \exp\left(-2\frac{K_i R_{bi}}{W}\right)}} - 1\right)\right]\frac{K_i R_{bi}}{W}(K_i - 1)} \quad (25)$$

Other Access Systems

For polling, where there are no collisions and the only noise power is thermal, the formulae are simpler and can be summed up by

$$C_{pelling} = W \ln\left(1 + \frac{P}{\rho N_0 W}\right) \quad (26)$$

$$P_{polling} = \rho N_0 W \left(2^{\frac{C}{W}} - 1\right) \quad (27)$$

$$\bar{P}_{polling} = \frac{1}{K}\sum_{i=1}^{M} K_i^2 R_{bi} N_0 \left(2^{\frac{R_{bi}}{W}} - 1\right) \quad (28)$$

Finally, we consider CDMA, where channel capacity is, in practical terms, unlimited. Therefore, it is the SNR, not the channel capacity, that features in the power expressions and is an important parameter in itself:

$$SNR = \frac{P_{CDMA}}{(K-1)P_{CDMA} + N_0 W} \quad (29)$$

$$P_{CDMA} = \frac{3WN_0 SNR}{3N - 2(K-1)SNR} \quad (30)$$

$$\bar{P}_{CDMA} = \frac{1}{K}\sum_{i=1}^{M} \frac{3K_i W N_0 SNR_i}{3\frac{W}{R_{bi}} - 2(K_i - 1)SNR_i} \quad (31)$$

$$SNR_i = \frac{P_{i(ALOHA)}(R_{bi}, K_i)}{(K-1)P_{i(ALOHA)}(R_{bi}, K_i) + N_0 W} \quad (32)$$

Comparative Study

The scene under investigation is an emergency ward in a hospital, where two patients are being simultaneously monitored for ECG, heart sound, and heart rate. From each patient a different set of data is collected, resulting in a total of 15 signals. For a quantities estimate of the model we stipulate the following set of values:

$\rho = 0.1$ (this low value facilitates the application of Taylor series approximations)

$N_0 = 10^{-15}$ W/Hz

ECG:	$R_b = 15{,}000$ b/s	$K = 9$
Heart Sound:	$R_b = 120{,}000$ b/s	$K = 4$
Heart Rate:	$R_b = 600$ b/s	$K = 2$

For comparison, we use Poisson assumption for the information arrival process.

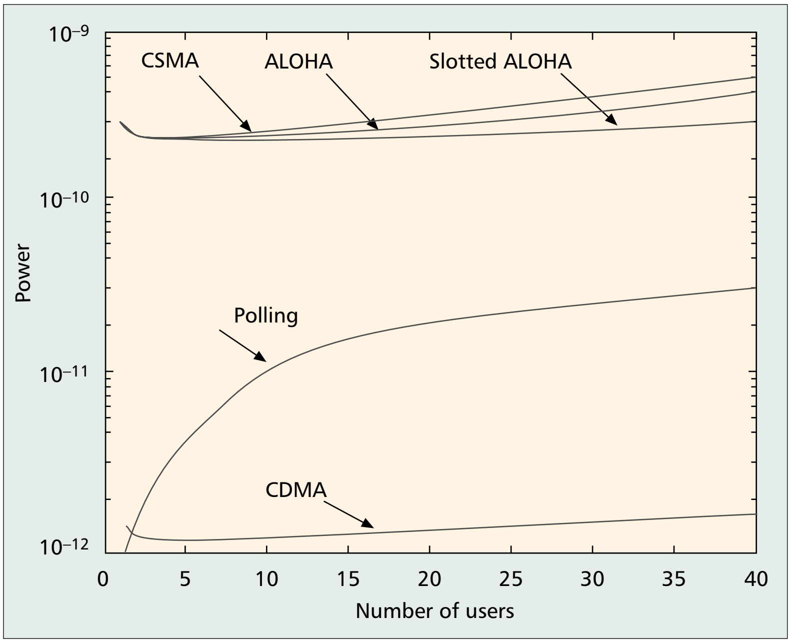
The required bandwidth (we use spreading of 10) is expressed as

$$W = 10\sum_{i=1}^{3} K_i R_{bi} = 6.162 \times 10^6.$$

Simple substitution in Eqs. 19–32 yields the results listed in Table 2.

The average power input vs. number of users

The scene under investigation is an emergency ward in a hospital, where two patients are being simultaneously monitored for ECG, heart sound and heart rate. From each patient a different set of data is collected resulting in a total of 15 signals.



■ Figure 1. *Power vs. number of users for constant data rate for five multiple access systems.*

Multiple access method	Power $\overline{P}$ (x 10^{-12} W)
ALOHA	37.276
Slotted ALOHA	34.501
CSMA	40.224
Polling	1.876
CDMA	0.576

■ **Table 2.** *Power vs. multiple access method.*

for a constant data rate for the five alternative multiple access systems (Fig. 1) and the complementary plot of average power vs. rate for 20 users (Fig. 2) summarize the broad comparative data well. While subtle differences exist between the random access systems, these three are in a different league from the other two systems in terms of power consumption. CDMA demonstrates distinctly lower power requirements than polling, an order of magnitude for most scenarios, while polling requires around 1/10th of the power of the random access systems.

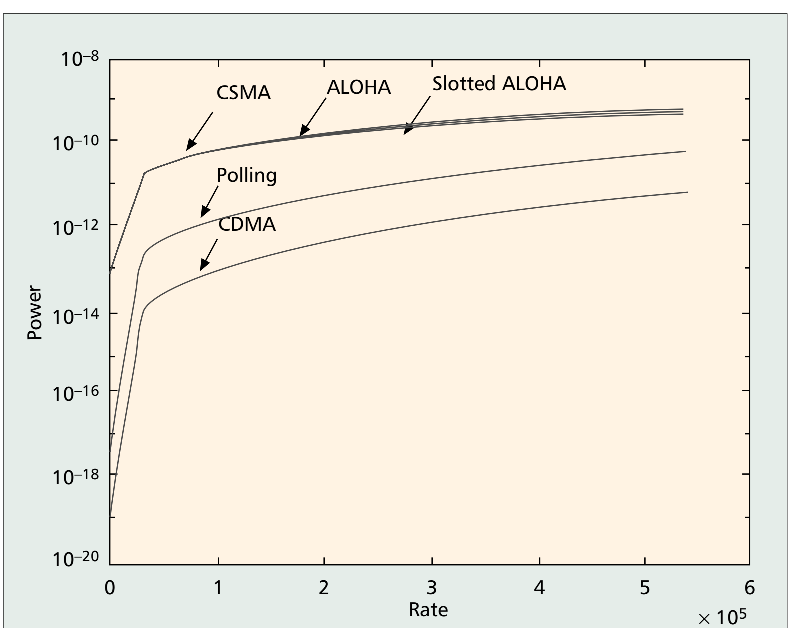
In the case of constant data rate, power consumption steadily rises very gradually for polling as the number of users increases, while in CDMA we observe a slight, but exponential, increase in power needs as more users are added. The power consumption of the three random access systems is clearly graded, with CSMA requiring more power than ALOHA, and slotted ALOHA showing the lowest requirements. The different needs of the three systems become more distinct as the number of users increases, growing from a few percent for 5–10 users to tens of percent for 40 users.

When the number of users is fixed at 20, the differences between the three random access systems is minimal for low data rates, rising as data rates increase to tens of percent at 500 kb/s. The gradation of the three systems is as described above. In all five systems, there is a sharp rise in power requirements as data rates increase from zero to around 30 kb/s, but the pattern of gradual increase in power consumption as data rates rise is similar in all. Thus, CDMA is consistently lower in its power consumption than polling for a given data rate, and polling, in turn, lags consistently behind the random access systems in power needs.

A qualification of the above must be made for all systems apart from polling: power consumption for a given data rate is higher for one or two users than for three, where the requirement is minimum, and increases steadily thereafter. The power consumption for one user is the same as for 20 users for CSMA, and more than for 40 for slotted ALOHA! This phenomenon is attributed to multiple access interference (MAI), which does not exist in polling, where the only noise source modeled was thermal.

In all multiple access systems, the power requirement skyrockets above a certain loading (combination of high data rates and large number of users). In this respect, it is the CSMA regime that proves to be most robust.

Finally, the total, average, minimum, and maximum powers were computed from the simulation and are presented in Table 2. All the data comply with the above analysis (except for a marginally and insignificantly higher minimum power requirement for CDMA in comparison with polling). It is notable that the minimum power requirement for all three random access regimes is the same.



■ Figure 2. *Power vs. data rate for constant number of users (20) for five multiple access systems.*

Conclusions

We have presented mathematical models to describe essential parameters of five alternative multiple access systems in wireless communications, and compared simulations of their performance in a medical environment. The systems were ALOHA, slotted ALOHA, CSMA, polling, and CDMA. The first three are random access systems. The medical environment is characterized by low power consumption requirements, very variable signals in terms of power and rate, and high demands of accuracy and reliability. In this preliminary model many potential noise and interference sources have not been included, not least intersymbol interference caused by multipath, but broad conclusions are in evidence. It should be noted that in the case of CSMA the choice of the ratio between propagation delay and packet time (chosen as two) is critical in determining performance results, and this regime may yield better results if the ratio is optimized.

Notwithstanding, the clear indication is that CDMA is the regime with lowest power requirements for all scenarios investigated. This is followed by the polling system, while the three random access systems are similar in performance, with consistent differences showing less power consumption for slotted ALOHA than for ALOHA. CSMA comes last in power efficiency, but further study may reveal better performance.

There appears to be great potential in pursuing this innovative idea, including clinical studies, investigation of other application areas, and deepening the study by sophisticating the model.

It should be noted that in the case of CSMA the choice of the ratio between propagation delay and packet time (chosen as two) is critical in determining performance results, and this regime may yield better results if the ratio is optimized.

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