Design and Evaluation of Wireless Health Care Information Systems in Developing Countries

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ABSTRACT

In many developing countries there is a tremendous demand for communication and information services, but conventional wired infrastructure to implement them is lacking. Wireless communication is easier and cheaper to introduce and to maintain, especially in remote and less developed areas. Based on the analysis of a distributed health care information system in Tanzania, the main requirements of wireless data communication in developing countries are derived and the suitability of wireless technologies is discussed. In order to cope with the limited bandwidth and unreliability of wireless communication links as well as to reduce communication costs, wireless information systems need to employ data replication. Therefore, this chapter also proposes a replication strategy for such wireless health care information systems in developing countries like Tanzania, and assesses its performance in terms of communication costs using workload characteristics from the Tanzanian case study.

1 INTRODUCTION

It is generally accepted that communication and information systems are major factors for economical and social development, but still are underdeveloped in many developing countries (Alleman et al. 94, Gardner 94, Meadows 94, Vishloff et al. 94, Ono 96, Thapisa 96). Financial, political and regulatory problems are some of the main obstacles to communication system development in developing countries (Ono 97, Ono 96, Anvekar et al. 96, Gardner 94). However, the demand for communication and information services in developing countries is increasing (Anvekar et al. 96, Meadows 94), but conventional copper wire infrastructures are too expensive to install and maintain in rural, less developed areas (Clontz 94, Ananasso 97, Gilder 95, Ramsay 95, Thapisa 96). Wireless communication systems offer greater flexibility in network design, faster deployment, and are more suitable in difficult terrain and climates (Javed et al. 94).

This chapter has three main contributions: it presents the application of a wireless health care information system in Tanzania, discusses appropriate wireless technologies to implement it, and proposes and evaluates replication management strategies to operate it efficiently at low costs. Section 2 describes the background and characteristics of the application, and highlights the benefits which health care can gain from the information system. Section 3 studies which wireless communication technology is suitable for such a distributed information system. We identify the main requirements of information systems' communication in developing countries and discuss to which extent they can be met by radio and satellite technology. Section 4 argues that wireless information systems need to employ data replication in order to reduce communication costs and to cope with the much lower bandwidth compared to wired networks. Possible replication strategies are evaluated in a simulation model, using the envisioned wireless health care information system as an illustrating example.

Further topics are relevant to the introduction of information systems in developing countries (e.g. political, social, cultural and regulatory issues, human resources, education, etc.), but are left to the literature[1] in order to concentrate on the organisational context and technical implementation.

2 APPLICATION ANALYSIS

Following previous related work in Tanzania, a seven month field study in 1996 was focused on analyzing the administration and information processing procedures of public health care facilities in Tanzania.

2.1 Background

Rural Tanzanian health care facilities can be classified in hospitals, health centers and dispensaries. They all have to cope with the poor infrastructure: hardly any of the sites have telephone or public power supply and the majority of the interconnecting roads are in a very bad condition. The few sites which are connected to the public power supply can hardly rely on it: Mtwara, one of the biggest cities in southern Tanzania, enjoys public electricity typically one day per week. Therefore the health facilities often have to rely on private electricity, i.e. diesel generators or water turbines. From 1985 to 1995 the telephone density in Tanzania increased from 0.22 telephones per 100 inhabitants to only 0.36 lines per 100 people, while the number of people waiting for a line more than doubled in the same period. Thus, Tanzania's defined

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[1] (Avgerou 88), (Walsham et al. 88), (Odedra et al. 93), (Ahamed, Lawrence 94), (Gardner 94), (Hull 94), (Levine 94), (Taylor 95), (Silva 95), (Curtis et al. 95), (Voraseth 95), (Sinha 95), (Petrazzini 95), (Thapisa 96), (Ono 96, 97).

goal of 1 line per 100 people by the year 2000 seems hard to reach (Kiula 94). In the neighbouring and many other African countries the situation is not much better (Odedra et al. 93). For comparison, note that in industrial countries like the USA, UK or Germany there are currently more than 50 phones per 100 inhabitants.

A *hospital* has 100 to 350 beds for inpatients but also serves outpatients. Next to the basic medical treatments its services usually include x-ray, surgery, etc. A hospital typically employs several doctors, often including specialists from overseas due to whom patients are frequently referred from one hospital to another. Moreover, a hospital is in charge of supervising a number of health centers and dispensaries.

A *health center* can be viewed as a small hospital. It has 15 to 60 beds and usually less advanced equipment and curative capabilities as well as less qualified staff. Health centers are meant to relieve the hospitals, especially by serving remarkable numbers of outpatients, but regularly they have to refer patients to a hospital.

A *dispensary* typically has no beds and thus no inpatients. Often the staff are less qualified than in health centers. The task of a dispensary is to examine and treat outpatients as far as possible with the knowledge and equipment at hand, and to either prescribe and sell appropriate drugs or refer the patients to a health center or hospital.

2.2 Benefits of a distributed health care information system

The field study revealed a lot of interactions between hospitals, health centers and dispensaries. They concern the administration and information processing among these facilities, and make a distributed health care information system desirable. Such a system will consist of local databases at each place which are to be interconnected by a wide area communication network. The local databases, even on their own, could be of great benefit for the facilities because:

- patient related information could be found and accessed very quickly. Often, the hand-written inpatient cards of discharged patients can not be found in time of need.
- statistics demanded by the government could be derived automatically, fast and accurately from the databases (instead of manually, slow and with mistakes as often found).
- further statistical evaluations are desired for decision support, effective management and controlling of treatments, drug prescriptions, costs, etc.
- epidemiological interdependencies could be revealed by evaluating the medical data.

Simple databases to assist certain statistical evaluations were designed and deployed at three missionary hospitals with lasting success (Nicola 96). Interconnecting the health facilities by a communication network has the potential to improve the public health care system:

- On the referral of a patient from one place to another there is usually no medical information passed on with him. Connecting the local databases would allow to transmit patient related data to the referral hospital prior to the arrival of the referred patient.
- Experience has shown that apart from referrals, patients that consult a health facility have stayed at a different hospital or health center at a previous time for a different reason. The patient's history is often an essential information for further treatment and could be found and accessed remotely. The exchange of patient related data also helps to avoid repetition of examinations and lab tests and thus saves time and money.
- Epidemiological evaluations make much more sense if they are carried out for a whole region than just for the catchment area of a single hospital. A distributed information system will be a valuable tool for regional or countrywide disease surveillance and supervision of the public health status. An example of current interest is the prevalence of HIV infection: evaluating the inpatient- and outpatient data shall reveal associations between HIV infections and residence of patients as well as associations between HIV infections and joining diseases.
- Since many of the health centers and dispensaries are located in remote areas where roads are in bad condition, visits by the supervising hospitals happen much less frequently than required. The ability to access remote data would allow a daily monitoring of the health work being done in those facilities. Furthermore, the amount of drugs needed and used by the health centers and dispensaries could be traced in a more reliable way. Since the hospitals are responsible for the financial and medical support, both a lack of drugs as well as wasting or stealing of drugs at the dispensaries are to be avoided.
- Generally, every hospital or health center is interested in statistical medical data of potentially any other place for various reasons like e.g. comparing the state of the own hospital to other hospitals or simply to know what's going on elsewhere. Though this point sounds vague it was highly emphasized by the people in charge.

- Looking into the future, a distributed health care information system could also be used for tele-medicine applications, like remote education and „support in action“ of low qualified staff, or remote tele-consultation and remote examinations, including the exchange of audio and visual data (Wright 96, Cabral, Kim 96).

Similar benefits have also been reported in the literature (Hutchison et al. 96, Jayaram et al. 96, Parsons 92, Yacubsohn 95), but mainly for industrial and semi-industrial countries, particularly their rural areas. The Stanford University Medical Center claims that wireless and mobile patient information systems can improve physicians efficiency by 30%, enable more personalized patient care, significantly reduce health care delivery costs and increase patient capacity by 30% (Brose 95). The effectiveness of patient records accessibility to support collaborative health care processes like referrals and consulting in rural West Virginia/USA has been evaluated in (Galfalvy et al. 95). Our findings demonstrate that interconnecting local health care information systems can be just as beneficial in developing countries.

2.3 Expected database size

The expected database size and transactional workload follows from the number of patients. Table 1 shows the in- and outpatient figures of four Tanzanian hospitals we visited in Nyangao, Ndanda, Peramiho and Mtwara:

		Nyangao	**Ndanda**	**Peramiho**	**Mtwara**
Admissions of Inpatients	1996	7.860	14.413	21.016	6.434
	1995	8.807	15.979	19.754	5.644
Admissions per Day	1996	26,2	48	70	21,45
	1995	29,3	53,26	65,85	18,8
Outpatients 1996	New Cases	60,635	61.215	86.375	26.502
	Re-Attendances	21.846	49.678	31.188	18.023
	Total	82.481	110.893	117.563	44.525
	Per Day	225	304	322	121
Outpatients 1995	New Cases	62.441	64.172	84.770	24.072
	Re-Attendances	27.351	56.974	41.020	16.844
	Total	89.798	121.146	125.790	40.916
	Per Day	246	332	345	112

Table 1: Number of patients at four Tanzanian hospitals

Additionally, various health centers and dispensaries were visited. Depending on size, a health center counts some 1.000 to 3.000 inpatient admissions and 20.000 to 150.000 outpatient attendances per year, while the dispensaries have 3.000 to 30.000 outpatients per year. Hence, 150.000 is a generous upper bound on the number of attendances per year at hospitals and health centres.

The above in- and outpatient figures were compared with statistics published in annual reports of other Tanzanian hospitals and some health facilities in Mozambique, Malawi and Uganda. The patient numbers above are quite representative for the whole of Tanzania, and similar characteristics are likely to be found in the adjacent East African countries.

In Tanzania we designed and implemented a prototypical patient database in MS-Access and found, that 150.000 attendances lead to approximately 35 MB of raw data. In a commercial database system this requires about 75 MB of storage space, which is an upper bound of the yearly database growth. This however does not include data replication yet (see section 4). Nevertheless, the experiments clarified that the data can be handled by low cost commodity database technology on PCs.

3 WIRELESS DATA COMMUNICATION TECHNOLOGIES FOR DEVELOPING COUNTRIES

General overviews of wireless data communication technologies can be found in (DeSimone, Nanda 95, Diehl et al. 95, Pahlavan et al. 94). The question to be addressed here is, which of those technologies are suitable for distributed information systems in developing countries.

3.1 Requirements

The main requirements arise from the application context:

- wide area communication
- easy and inexpensive installation of the wireless network
- low running cost for operating the network
- easy operation and maintenance of the network, since there are too few service specialists in remote areas of developing countries
- decoupled (but not necessarily mobile) computing (i.e. users can connect to the system anytime and anywhere but do not change their location *while* being connected)
- sufficient network performance (i.e. throughput & communication delay & availability & reliability) to ensure application functionality
- the communication system must be expandable to allow for many sites to join the distributed information system in future

Several of these requirements match with the list of *rural telecommunication equipment requirements* in (Vishloff et al. 94), i.e. they apply not only to Tanzania but to many developing countries. The first condition reduces the techniques to be considered to wireless WAN systems which are in general HF/VHF radio techniques, analogue and digital cellular architectures and satellite services. All of these systems support decoupled computing. Cellular architectures violate the demand of cost effective installation and operation because they require a base station to be installed in every cell which does not pay off in remote areas of low user density (Maral 94, Vishloff et al. 94). Thus, only radio and satellite systems will be discussed here further.

3.2 Existing wireless information systems in developing countries

The aim of the non profit organisations VITA (Volunteers in Technical Assistance) and SatelLife is to provide low-cost data-communication and information services in developing countries (Vita 97, SatelLife 97). The general approaches of VITA's *VITACOMM* system and SatelLife's *HealthNet* are similar: Both organisations employ „small“ LEO (low earth orbit) satellites, amateur packet radio techniques and conventional telecommunication structures if existent (see Appendix C for details). Neither system provides a global coverage of real time services but delayed store-and-forward data messaging only. This type of service is inappropriate as a communication network for distributed database systems. Hence, radio or satellite systems need to be employed in a different manner.

3.3 Packet radio vs. satellite systems

PACTOR and packet radio are digital modes of amateur radio communications[2], which take a data stream from a computer and send it in packets via radio frequencies to another station similarly equipped (Kenney 97, Leiner et al. 87, Karn et al. 85, Karn 92). Details are given in Appendix A. Commercial satellite systems such as *Iridium*, *Globalstar*, *Odyssey*, or *ICO-P,* are currently being developed to provide world wide phone services, but they also offer wireless data communication[3], e.g. through satellite modems. The various satellite systems are described in Appendix B. Since most of the satellite systems are still under development, it is very difficult to predict which system will provide the best quality of tele- and data-communication services at a reasonable price. From the system characteristics we believe that *Iridium* is the most promising satellite system for rapid introduction of ubiquitous communication in developing countries. *Iridium*'s crucial advantage over the other systems

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[2] Packet radio is used on VHF radio; PACTOR is most popular on HF radio. In the following we use „packet“ as a generic term for both.

[3] See (Abrishamkar, Siveski 96), (Ananasso, Carosi 94), (Ananasso 97), (Comparetto, Ramirez 97), (Westerveld 96), (Johannsen 95), (Johannsen, Park 95), (Maral 94), and (Wisloff 96) for details.

(except *Teledesic*) is that its inter-satellite link technology will allow service in (developing) countries without any terrestrial wireline infrastructure.

The advantages and disadvantages of radio and satellite systems are compared in table 2. The main arguments for radio are the low costs for installation and operation. In turn, high initial and high running costs are major drawbacks of satellite systems, which is also criticised in (Vishloff et al.94).

PACTOR / Packet Radio	**Satellite systems**
☺ cheap to buy	☹ expensive to buy
☺ low running costs	☹ comparatively high running costs
☺ available now	😐 still under development (except *Inmarsat*)
☺ radio call is common for voice communication in developing countries	😐 very new technology
😐 amateur technology	😐 professional high tech
☹ uncertain development	☺ likely to become cheaper, more advanced, widely spread and common
☹ maintenance to be done by users	☺ network maintenance by satellite company
☹ low reliability compared to satellite systems	☺ a constantly very high reliability and...
☹ quality of performance can vary widely	☺ ...availability is promised
😐 typically 1.2 kbps or 2.4 kbps	😐 typically 2.4 kbps or 9.6 kbps
☹ in some places a license is required	☺ no regulations for end users
☺ broadcast to multiple sites possible	☹ no real broadcast
😐 expandable	☺ very easy to expand
☹ in some places not allowed for commercial use	☺ seamless integration with terrestrial phone systems world wide
	☺ *Inmarsat* has experience in tele-medicine

Table 2: Advantages and disadvantages of packet radio and satellite systems

The main advantages of satellite systems over radio are constantly „guaranteed“ throughput, reliability and availability, as well as a very promising future. Personal satellite communication is going to be a several billion dollar market for years to come where hundreds of millions of customers are expected to be served (Javed et al. 96). Thus, a professional and competitive development will continue in order to meet the customer's demands, to allow low prices, and to strive for a continuously increasing quality of service. Furthermore, the seamless integration with terrestrial phone networks world wide - whether wired or wireless - will conveniently integrate a satellite phone user into the world of information and communication. Currently a remarkable decrease of charges is taking place on the market of cellular wireless phone systems. A similar development can be expected for satellite phones as the number of customers and the number of competing companies grow. Additionally, the network infrastructure itself is maintained by the satellite system operator rather than by the users themselves.

3.4 Conclusion

Considering the current status and the future development of availability, running costs and quality of service, we conclude that in the short-term packet radio is the most feasible data communication infrastructure for East African countries (and possibly for other developing countries as well).

However, in the medium- and long-term global satellite systems are the most favourable tele- and data communication infrastructure for developing countries. This is because of their high quality of service, decreasing running costs, integration with existing networks, and their major role in future communications. In general, this view is shared by (Ramsay 95, Chasia 95). Furthermore, there is a growing awareness that the cheapest technology is not necessarily the best choice, because by utilising the latest technology, developing nations could ‘leapfrog’ technological stages followed in many developed countries and ensure that their communication infrastructure is a competitive and durable state-of-the-art, able to participate in future innovations.

Although a trend from packet radio to satellite systems can be expected, their common drawback is a very low transmission capacity compared to wired networks. Therefore, our approach to design wireless information systems is to tackle the limited bandwidth problem in general (through application oriented replication), while abstracting from other technical details of either technology.

4 REPLICA MANAGEMENT

The objective of data replication is to increase data availability in the presence of site or communication failures, and to decrease data retrieval costs by reading local copies if possible. When and where to replicate data and how to update replicas to maintain an acceptable degree of mutual consistency is of high importance, because skilful replication can substantially reduce network traffic while inadequate replica management can cause severe communication overhead (Gallersdörfer, Nicola 95). In wireless information systems this is particularly crucial, not only to keep communication costs low, but also to relieve the low bandwidth communication links in order to avoid network congestion and bottleneck symptoms.

Based on the application analysis, replication is considered to reduce the number of remote accesses to patients' medical histories. Typically, there is attendance independent data (i.e. *Name*, *Date of Birth*, *Place of Birth*, *Domicile*,...) and attendance related data (i.e. *Date of Admission*, *Ward, Diagnoses, Drugs given*, *Operations*, *Treatments*, *Date of Discharge*, *State of Discharge*,...). Each patient may attend a health facility several times and during one attendance he may get several drugs, treatments, etc. due to several diagnoses. There is one set of attendance related data for every attendance (stay) at a health facility. A patient's complete medical history comprises his attendance independent data as well as all his (sets of) attendance related data.

The application analysis revealed 3 characteristics concerning the typical access of patient data:

(1) Typically, once a patient's data has been inserted into a local database, it will hardly ever get changed after the patient's discharge, because new attendances will be *appended* to the patient's history.

(2) A patient's medical history will typically only be read or extended at a health facility which the patient is currently attending, i.e. at a given point in time, a patient's data will be accessed at at most one local database.

(3) When a (part of a) patient's history is replicated from a local database at site A to site B, the replica will be *read-only*, because site B will not change any data related to a patient's attendance at A. Rather, data related to the attendance at B will be inserted. If the data related to the patient's attendance at site A ever needed to be updated, such an update would always take place at the 'original home site' (primary site) of the attendance.

Basically, these properties imply that there will be hardly any concurrent access to a patient's data. Moreover, property (3) implies that processing updates according to the primary copy approach[4] fits the application in a natural way. However, due to the great number of patients in the distributed health system and their quite unpredictable behaviour concerning when and where to visit health facilities, it does not make sense to impose a predefined and static replication scheme on the distributed database. Instead, data should be replicated *dynamically*. Various dynamic replication schemes have been proposed in literature: (Acharya, Zdonik 93) describe a replication scheme that uses finite automatons to learn and predict access patterns due to which replicas are created or deleted. (Faiz, Zaslavsky 95) present a so-called virtual primary copy algorithms to address replica management in mobile computing. (Little, McCue 94) dynamically recompute the replica placement schema, taking into account the read/write

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[4] See (Stonebreaker 79), (Elmasri, Navathe 94) p.722f for details.

ratios and the sites' characteristics regarding availability. Yet other dynamic replication schemes focus on load balancing between database sites (Lee, Hua 94), or higher reduction of communication costs than with static replication (Wolfson et al. 97).

These approaches of dynamic replication seem too complex to be practical for the application at hand, because experience has shown that simplicity is essential for successful operation of information technology in developing countries like Tanzania. Hence, we propose a *central site replication* scheme, which exploits the application characteristics mentioned above for simple but effective replica management.

4.1 Central site replication

The central site replication approach is to have a designated central database system which serves as a replication server for the whole distributed system (Figure 1).

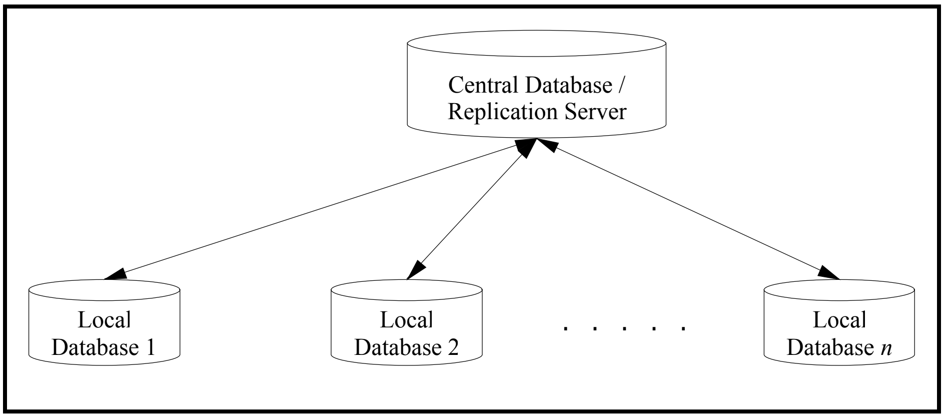

Figure 1: Central site replication

Each local database manages the data of its local patients, retaining its autonomy. Regularly local database updates are transmitted in a batch to the central site. Thus, the contents of the central database is the union of the *n* local databases. If a patient visits a health facility for the first time there will be no information on him in the local database, but his complete medical history can be downloaded from the central site and kept as a local replica. When the patient returns to the health facility at a later date, his medical history is available locally and communication with the central site can be avoided. However, the local replica of the patient's history might be out of date (i.e. incomplete) if the patient has attended one or more different health facilities since his last visit. Refreshment of stale replicas (i.e. completion of the patient's history) can be performed *eagerly* or *on demand*.

Refreshment on demand leaves the decision when to check at the central site whether or not a local replica is stale to the local sites. The idea is that data will be replicated *dynamically and incrementally* as patient histories are transmitted on user demand from the central site to a local database. Once data related to a patient or an attendance has been transmitted due to a user's request, a secondary copy (a replica) can be installed at the local database at *no extra communication costs*. This is very important considering the aim to reduce communication.

Consider a patient who visits a hospital but has attended other health facilities in the past. In such cases a remote access to the central site is necessary to obtain the complete patient's history. This is a critical drawback of replication on demand, because response times are lengthened by remote access, or even worse, the central site might be unavailable. The approach of e*ager refreshment* is to update locally replicated data whenever a corresponding update arrives at the central site. This requires the central site to keep track of which sites downloaded which data items, so that it can propagate the updates/inserts to the affected sites. Thus, whenever the patient visits a site he has attended before, his complete medical history is available locally. Only on attendances at sites he has never visited before, remote access is necessary to retrieve the patient's history. However, if a patient once attended a site he never visits again, replicas are transmitted to that site although they will never be used. These properties of eager replication indicate that higher availability is bought by increased communication (costs). The increased communication caused by eager replication can be reduced by delaying and batching several replication messages having the same destination into one (Nicola, Jarke 98).

The central site replication raises some of the advantages and drawbacks commonly related to centralized database systems:

☹ The central database might be become very large.

☹ If the central site fails, the replication and remote access services for the whole system are suspended.

☹ Due to its size and importance, the central site needs more sophisticated maintenance than the local databases.

☹ The central site could be a potential performance bottleneck.

☺ Every patient's complete medical history can be found easily at the central site.

☺ Recovery and replica refreshment after site failures or elected down times are much simpler than in the distributed case.

☺ Supervision of health facilities as well as multi-site statistical and epidemiological evaluations are much simpler, faster and cheaper to execute connecting to the central site only.

☺ Data security and privacy can be ensured more easily than in a distributed system.

4.2 Evaluation

The quality of the replica management strategies presented above was assessed by a simple discrete event driven simulation with the number of required communication connections and the local data availability as performance criteria. Availability is defined here as the percentage of queries (for complete patients' histories), which can be answered locally, as opposed to those which involve remote access to the central site.

In the simulation a total number of 150.000 patients is considered, who visit 30 sites one or several times. Since patients exhibit a certain locality concerning the health facilities they visit, each patient i is assigned a 'personal' subset of m_i sites, where m_i is drawn for every patient i as a random number uniformly distributed between 1 and 5. The patient's m_i personal sites are drawn randomly from the set of all sites. Every patient has a first attendance at a site which is drawn randomly from his set of personal sites. Then *max_re_att* times a patient is picked randomly from the list of patients for a re-attendance at a site which is again drawn randomly from his personal sites. This creates a scenario in which some patients have more attendances than others, and some patients visit always the same site(s) while others often visit different sites. These are quite typical characteristics of patient behaviour in Tanzania. Although no such model can *exactly* match the actual patient behaviour, this model of patient behaviour and workload is at least sufficiently accurate to reveal the *relative* performance differences between no-replication and central site replication with refreshment on demand or eager refreshment.

Figure 2 shows the total number of communication connections required, depending on the overall number of re-attendances.

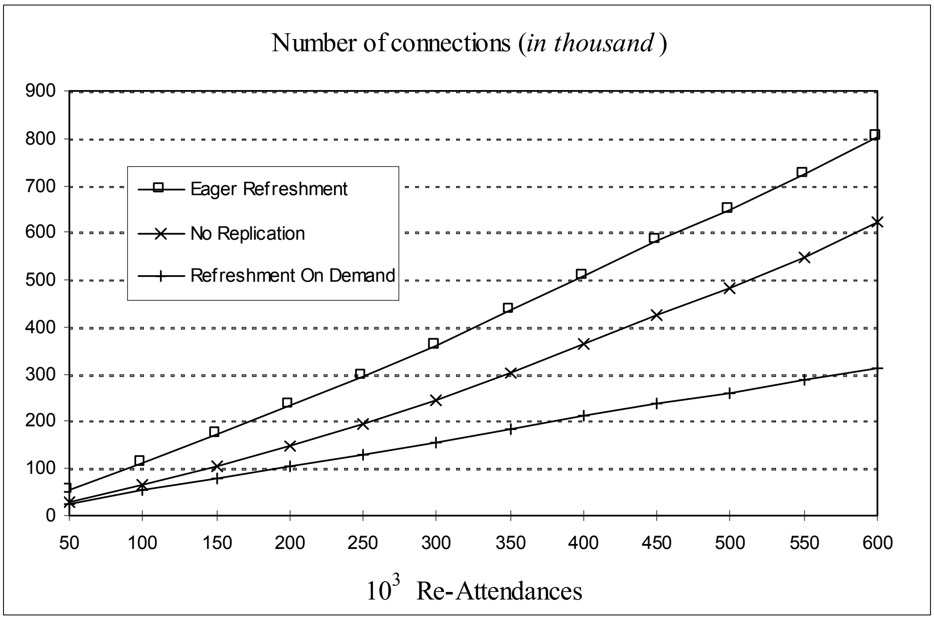

Figure 2: Number of connections

As it turns out, the number of messages grows approximately linearly with the number of re-attendances. Sensitivity analysis revealed that it grows linearly with the number of patients as well[5]. *Eager refreshment* creates the highest communication traffic, even remarkably higher than *no replication*, because eager replication also maintains secondary copies that might rarely or never be used, causing pure overhead. *Refreshment on demand* causes considerably less network traffic than *no replication*, because replicas are created at no extra communication cost. Hence, replication on demand can never increase but only decrease network traffic due to improved local data availability. Furthermore, refreshment on demand provides a constant level of local data availability as the number of re-attendances grows (Figure 3). In fact, the availability using replication on demand equals the probability that a patient visits the same site two or more times in a row, which is independent of the number of re-attendances.

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[5] Unfortunately, a complete description of the sensitivity analysis and confidence intervals for the simulations is beyond the scope of this chapter.

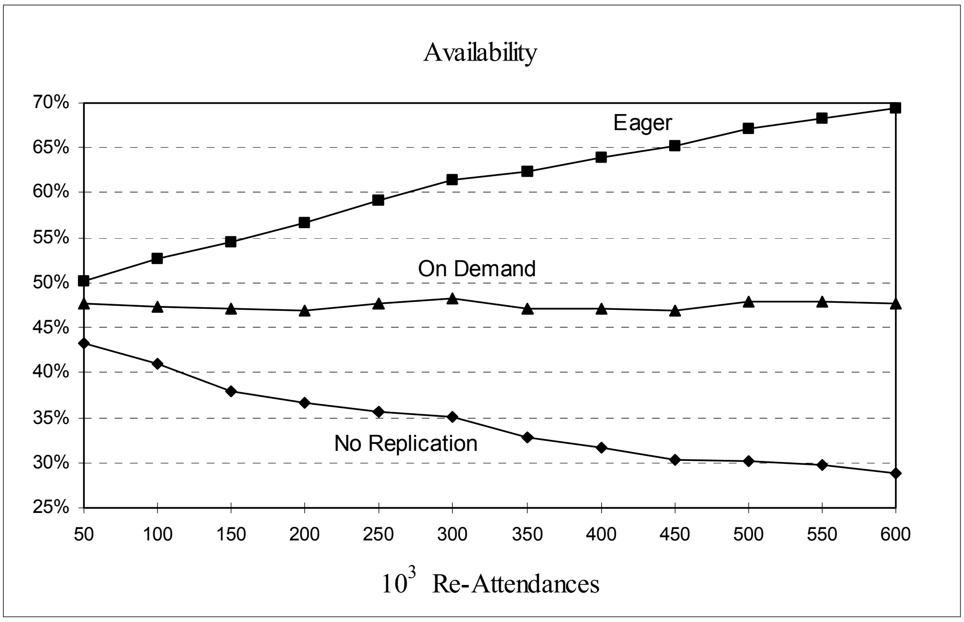

Figure 3: Local data availability using eager or on demand strategies

Eager refreshment causes the availability to increase with a growing number of re-attendances because the higher the number of re-attendances the higher the probability that a patient visits a site he has visited before. As the number of re-attendances gets very large, availability asymptotically converges towards 100%, because after a sufficient number of re-attendances all patients will have visited all of their personal sites at least once. Thereafter, all the sites will be kept up-to-date eagerly so that a patient's history will always be available locally.

With *no replication*, availability decreases and converges towards a value $v > 0$, because as the re-attendances increase, most patients will have visited two or more different sites, neither of which ever hold their complete medical history without replication. However, v is greater than 0, because some patients have only 1 personal site which always holds their complete medical record, even without replication.

Concluding, replication on demand is a favourable replication strategy for wireless information systems because it leads to considerably less communication and increased availability, compared to no replication. Applications that demand even higher availability can employ eager replication at the cost of additional communication. For the application of a wireless health care information system in Tanzania replication on demand seems to be a suitable trade-off between availability and communication, because the attainable availability will allow a sufficient quality of service while communication costs are as low as possible. Distributed versions of eager and on-demand replication have been proposed in (Nicola, Jarke 98). However, the advantages of the central site regarding security, privacy, maintainability and supervision make this approach more suitable for developing countries like Tanzania than more complex distributed mechanisms.

5 SUMMARY

This chapter dealt with wireless information systems in developing countries. As a sample application it presented the benefits, characteristics and requirements of a distributed health care system in Tanzania. Regarding the suitability of wireless technology for developing countries, it discussed the advantages and drawbacks of amateur radio and commercial satellite systems. The conclusion is that packet radio is currently quite attractive for use in developing countries because of its very low costs, but the remarkable development of satellite systems will soon provide more sophisticated, ubiquitous communication services. However, the low bandwidth of either wireless technology as well as communication costs force wireless information systems to reduce communication as far as possible. This can be achieved through skilful replication. Practicality considerations recommend *central site replication* to ensure the required maintainability and data security. We sketched two replica management strategies in a central server system, and showed how to use them in a health care information system proposed for developing countries like Tanzania. A simple simulation identified that wireless replica management faces a trade-off between data availability and communication costs, and concluded that *replication on demand* is a suitable choice for wireless information systems because it offers fair data availability and low communication costs at the same time.

Although this research is based on the case study in Tanzania, the discussion concerning requirements, wireless technologies, and replica management might be also worthwhile to consider when designing information systems in other developing countries.

APPENDIX A. PACTOR AND PACKET RADIO

In general, PACTOR and packet radio correspond to computer *tele*communications: The telephone modem is replaced by a *terminal node controller* (TNC), the telephone is replaced by a commonly available radio transceiver, and the phone system is replaced by the radio waves. A TNC (usually connected to a computer via an RS-232 port) assembles a packet of data received from the computer, computes an error check for the packet, modulates it into audio frequencies and puts out appropriate signals to transmit the packet over the connected radio. It also reverses the process: translating the audio signals that the connected radio receives into a byte stream that is then sent to the computer. Packet radio is commonly used on VHF radio (very high frequency) with a communication range of 10 to 30 miles and data rates of 1.2, 2.4 or 9.6 kbps. Packet radio stations can act as repeaters to compose a packet network, through which the communication range can be extended at will. PACTOR is the most popular mode on HF radio (high frequency). Its range can be 1000 miles and more, but at rates of 250 bps to max. 1.2 kbps only. A complete radio station package (including TNC, transceiver and accessories) is between US$ 1000,- and 2000,-.

APPENDIX B. COMMERCIAL SATELLITE SYSTEMS

Although emerging satellite technology is an intriguing field, a detailed elaboration is beyond the scope of this paper[6]. Roughly, satellite systems can be classified by the kind of satellites and their orbits:

Geo-stationary (GEO) satellites always stay at a fixed location in an equatorial orbit and thus provide a non-stop covering for a certain region (about 1/3 of the earth's surface). However, performance is poor for urban and polar regions. The great altitude of GEO satellites entails the need to use large terminals and antennas, and causes a (fixed) propagation delay of 250 ms.

Low earth orbit (LEO) satellites constantly circle around the earth at low heights (700-1500 km). On their way round they constantly project cells onto the earth's surface which is similar to cellular architectures. However, the cells are moving so that even users who do not change their location have to be handed over. The low altitudes imply that more satellites are needed for global coverage and lightweight handheld terminals can be used. In general, LEO systems are more complex due to the high number of satellites and frequent handovers.

Medium earth orbit (MEO) or *intermediate circular orbit* (ICO) satellites represent an orbital and architectural compromise between LEOs and GEOs. For example, MEO propagation delay is less than GEO but more than LEO; MEO requires less handovers than LEO but more than GEO; and so on. The most important characteristics of the three groups of satellite systems are summarized[7] in table 3:

	LEO	***MEO***	***GEO***
Orbit	700 - 1500 km	10.000 - 14.000 km	35.786 km
Propagation delay	5 - 35 ms	50- 125 ms	250 ms
No. of satellites for global coverage	40 - 70	10 - 15	3-4
Satellite visibility	10 - 20 minutes	several hours	non-stop
Satellite system complexity	high	medium	low
Satellite size/weight	low	medium	high
Satellite lifetime	low (4 - 7 years)	medium	high (10-20 years)
Handovers	very frequent	occasionally	hardly any

Table 3: Satellite system types

So-called *small* LEO systems (e.g. *Starsys*, *LeoSat*, *VitaSat*, etc.) typically consist of 1 to 6 very small and very low orbit satellites that are used for delayed store-and-forward data messaging. They do not provide real-time or online service and no truly global coverage. All commercial satellite systems with global coverage (except *Inmarsat*) are still under development. The characteristics of the most promising commercial satellite systems are given in table 4:

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[6] See (Abrishamkar, Siveski 96), (Ananasso, Carosi 94), (Ananasso 97), (Comparetto, Ramirez 97), (Westerveld 96), (Johannsen 95), (Johannsen, Park 95), (Maral 94), and (Wisloff 96).

[7] For details on highly elliptical orbit (HEO) systems please refer to the literature.

System:	**Inmarsat**	**Odyssey**	**ICO-P**	**Ellipso**	**Iridium**	**Globalstar**	**Teledesic**
Company:	Inmarsat	TRW	ICO Global	Ellipsat Corp.	Motorola	Qualcomm, Loral Inc.	Bill Gates, G. McGaw
Orbit type	GEO	MEO	MEO	HEO	LEO	LEO	LEO
Altitude [km]	35.786	10.360	10.400	520-8040	780	1.414	700
No. of satellites	5	12	10/12	24	66	48	840 (!)
Satellite weight	1900 kg	2000 kg	2000 kg	500 kg	690 kg	450 kg	700 kg
Data rate [Kbit/s]	2.4	9.6	2.4	9.6	2.4	9.6	16-2048
Channel access	FDMA	CDMA	TDMA	CDMA	TDMA/ FDMA	CDMA	FDMA/ ATDMA
Inter satellite links	no	no	no	no	yes	no	yes
Terminal price (US$)	10.000 - 40.000	250 - 450	500	600	500 - 2500	700	?
Price per minute (US$)	4 - 8	0.65	2.0	0.5	3.0	0.3	?
Monthly charge (US$)	?	?	30	?	50	30	?
Start of service	1996	1998	2000	1998	1998	1998	2002
System cost (Billion US $)	?	1.8	2.6	0.5	3.5	2.0	9.6

Table 4: Commercial satellite systems

The prices in the table above are still subject to change and may depend on the service provider. It is commonly accepted that GEO systems are not suited to provide ubiquitous communication with small terminals (Ananasso 97, Comparetto et al. 97). (Gilder 94) concludes in his discussion of satellite systems that *Iridium* will be too expensive for voice communication and too narrow banded for data communication, and that *Globalstar* is „his favourite". By analysing more than 200 low level technical system parameters, (Johannsen 95) argues that the MEO systems *Odyssey* and *ICO-P* emerge as the best satellite systems for mobile and ubiquitous communication. (Huber 94) concludes that *Iridium* appears, along with *ICO-P* and *Globalstar*, to have the most realistic chance of success in the year 2000. *Teledesic* is different from the other systems in that it does not aim at voice communication but broadband data communication only. However, the huge number of satellites and the resulting system complexity is seen as a serious obstacle for system implementation. Leaving the prices apart we believe that *Iridium* is the most promising satellite system for rapid introduction of ubiquitous communication in developing countries, because a major advantage over the other systems (except Teledesic) is that the inter-satellite link technology allows *Iridium* to provide service in countries without any terrestrial wireline infrastructure. In fact, one earth gateway is sufficient to run the *Iridium* system, while the other systems depend on a ground infrastructure of gateways all over the world.

The commercial satellite systems will start their service in a certain year but then it will still take time until their satellite constellation is complete to establish world wide coverage entirely. To quickly gain revenue the satellite companies will supply the mass market in the industrial countries first, while rural areas of developing countries will be covered when the satellite constellation is eventually completed. (Johannsen 95) mentioned that *Globalstar* will cover only the USA in its first phase of operation.

APPENDIX C. EXISTING WIRELESS INFORMATION SYSTEMS IN DEVELOPING COUNTRIES

SatelLife's HealthNet

SatelLife's main project is HealthNet, a communication system to serve about 4000 health care workers in 30 developing countries. HealthNet's cornerstone is a small LEO satellite („HealthSat-2") in a polar orbit which is capable of store-and-forward data communication at 9.6 kbps. From a given position on earth the satellite is visible usually 4 times a day for about 13 minutes, during which up- or downloading of data can take place. Amateur packet radio networks and the amateur email network FIDONET are used to supplement the LEO system with terrestrial structures. Individual users link to the network via nodes in each country where HealthNet is operating. In Tanzania there are currently three HealthNet nodes (in the northern cities Mwanza, Dar es Salaam and Ifakara). Furthermore, SatelLife intends to install an HF/VHF radio network in the Mwanza area, using standard amateur radio hardware and customised software written by SatelLife.

The main information services HealthNet is providing are email, electronic conferences, distribution of health care related electronic publications, off-line access to medical expert databases and medical libraries, and collection and distribution of medical data (SatelLife 97).

VITA's VITACOMM

VITA's global communication system VITACOMM for developing countries consists of VITASAT, a system of three small LEO satellites, VITAPAC, a number of independent radio packet networks, and VITANET, an email system using conventional telephone networks where existent. Similar to HealthNet's satellite, VITASAT's LEOs act like orbiting postmen, collecting and distributing messages to and from ground stations visible in the satellite's footprint. It takes VITASAT typically „90 minutes to 12 hours" to forward a message to its proper destination anywhere on the world. A VITASAT ground station equipment costs about US$ 3.500 plus the price for a personal computer. The running costs are $50 per month for up to 100K of data transferred. A VITAPAC station consisting of a PC, a TNC, a radio and an antenna is about $4000 - $10.000.

VITACOMM provides information services to supports any kind of development issues like health information and education, administrative and logistic support, disaster prevention and response, economical development, protection of the environment, etc. (Vita 97).

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