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Bilstrup U, Sjöberg K, Svensson B, Wiberg P. Capacity limitations in wireless sensor networks. In: ETFA 2003: 2003 IEEE Conference on Emerging Technologies and Factory Automation, September 16-19, 2003, Lisbon, Portugal : proceedings. Piscataway, N.J.: IEEE; 2003. p. 529-536 vol. 1.

DOI: <http://dx.doi.org/10.1109/ETFA.2003.1247752>

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Capacity Limitations in Wireless Sensor Networks

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Abstract – It is expected that wireless sensor network will be used in home automation and industrial manufacturing in the future. The main driving forces for wireless sensor networks are fault tolerance, energy gain and spatial capacity gain. Unfortunately, an often forgotten issue is the capacity limits that the network topology of a wireless sensor network represents. In this paper we identify gains, losses and limitations in a wireless sensor network, using a simplified theoretical network model. Especially, we want to point out the stringent capacity limitations that this simplified network model provide. Where a comparison between the locality of the performed information exchange and the average capacity available for each node is the main contribution.

I. INTRODUCTION

A wireless sensor network provides a suitable interface for interaction, physical control, information harvesting and exchange. In the area of factory automation, there are especially applications such as; environment monitoring, test, information exchange, information gathering, control, security, object tagging, and identification.

A typical application can be an automatic guided vehicle where a wireless sensor network is used for positioning, guidance and interaction with surrounding machines and robots. In the extreme case the product itself can be equipped with a radio node, making it possible for the assembly robots to interact with the product during the assembly. This would make it possible to conduct tests, software downloads and identification during assembly process of complex products, e.g., in a car assembly line.

A. Previous work

Wireless sensor networks have been proposed in a number of papers [1, 2, 3, 4, 5, 6], recently. Both military information gathering applications such as distributed sensor fields in the battlefield and civilian applications such as biological, earth and environmental monitoring applications are proposed. The first research in the area of wireless sensor networks was performed during the early seventies. During which a number of papers regarding the performance of different media access methods were

published, especially [7, 8, 9]. The aspect of real-time traffic such as voice and video streams in wireless networks is considered in [10]. This type of wireless networks were given the name "3M", i.e., multimedia, multihop and mobile. The evolutions in low power micro-sensors, actuators, embedded processors, and radios are the necessary technology steps enabling large scale wireless sensor network with huge number of nodes [6]. These can be extremely small, in some cases as small as dust [4]. The signal processing in this kind of wireless sensor networks is assumed to be distributed [11], as will the co-ordination of the wireless sensor network.

II. FAULT TOLERANCE

One of the first theoretical works on packet switched networks with fault tolerance was Baran's work in 1964 [12]. A large variety of network topologies can be created but they all end up into two main classes; the star topology or the distributed topology. The star topology is more vulnerable to a failure of the central node or of the single link from each node to the central node, than the distributed network topology. The main advantage with the distributed network topology is that it provides multiple paths over which the communication can take place.

The redundancy level R in a distributed network is defined as the link to node ratio (connectivity) in an array of nodes. A minimum connectivity is used as a reference and is said to have a redundancy level of one $R=1$, e.g., a ring or linear network Figure 1a. A grid or mesh can have a redundancy level of two, three, or four, etc as seen in figure 1 b to d.

Figure 1. Connectivity and redundancy level. a) Linear network $R=1$. b) Mesh $R=2$. c) Hexagonal mesh $R=3$. d) Mesh $R=4$.

The fault tolerance present in networks with $R > 1$, prevents a total network collapse if a single node or link fails. In a wireless sensor network, link loss is caused by node distribution, mobility and the stochastic behaviour of the wireless medium. The achievable connectivity between nodes is closely related to the maximum transmission range of the transmitter and the node density per area unit, i.e., the local interference level.

A lattice percolation [13] simulation of a network topology gives a good estimate of how the redundancy level impacts the connectivity. Instead of considering percolation paths we simply consider the largest fraction of nodes in connection (G_{max}) versus the probability for link failure ($P_{destroy}$). A symmetric network topology is created out of 100 nodes with a certain redundancy level (R). Then each link is destroyed with a certain probability $P_{destroy}$. The graph in Figure 2, G_{max} versus $P_{destroy}$, is shown for different values of R . As can be seen, already $R=2$ and $R=3$ introduce a rather high persistence against message delivery failure in a distributed topology, if compared with networks with $R=1$, e.g., linear, ring or star topology.

Figure 2. Fraction of nodes in connection G_{max} versus link failure probability $P_{destroy}$ for different redundancy levels R .

The multi-path capability provides persistence against interference and intentional hostile jammers [14]. It is the main driving force for the development and deployment of wireless sensor networks, especially for hostile environments such as in a factory [15, 16].

III. GAINS AND LOSSES

In this section a comparison of different parameters such as delay, energy, capacity and error probability rate, is compiled. This comparison is performed with a single hop topology as reference and

this clearly identifies a trade-off situation between these different parameters. In order to identify and provide properties of a wireless sensor network a simple theoretical network model is used, based on a regular mesh network.

Energy analysis seems to argue for an infinite number of hops over the smallest possible energy path. In reality however, the node density and the sometimes random distribution of repeater nodes between the source and the destination node limits the energy gain that can be achieved. In any case, the non-linear attenuation function for electromagnetic wave propagation enables a substantial amount of energy gain by relaying messages over a multihop path, if compared with single hop transmission.

Theoretical models and practical measurements have shown that the average received signal power P_r decreases as a function of the transmitter-receiver distance r [16, 17, 18]. The average large-scale path loss L_p , for an arbitrary transmitter-receiver separation is expressed as a function of the distance r and the path-loss rate exponent n as in equation (1), where r_0 is a reference distance.

$$L_p(r, n) = L_f(r_0) + 10n \log_{10} \left(\frac{r}{r_0} \right) \quad (1)$$

The path loss exponent n indicates the rate at which the path loss increases with the distance r . The attenuation model in (1) has been shown to be applicable for both indoor and outdoor environments. Experimental results indicates [16, 18] that typical outdoor cellular mobile systems have a path loss exponent of $3.5 < n < 4$ and indoor channels have a path loss exponent of $2 < n < 6$. The path loss up to the reference distance r_0 is either determined from measurement close to the transmitter antenna or by the free space propagation loss equation according to:

$$L_f(r) = \frac{G_t G_r \lambda^2}{4\pi^2 r^2} \quad (2)$$

The G_t and G_r in (2) are the antenna gains at the transmitter and receiver respectively. The r_0 distance should be greater than the near field of the antenna (Fraunhofer distance).

Equation (1) is used to calculate the received power P_r according to:

$$P_r = 10 \log_{10}(P_t) + L_p(r, n) \quad (3)$$

The power required to transmit a message from node m_i to the receiving node m_j over a distance r is denoted P_t . The area covered by the transmission is approximately $2\pi r^2$, assuming an isotropic antenna. This transmission contaminates other concurrent transmissions with interference, i.e., all receiving nodes inside this area experience co-channel interference.

In a real wireless sensor network, the reception area is contaminated with interference from concurrent transmissions. The border of a transmitter's reception area is determined by (4), the signal to interference ratio (SIR), at the receiver. The received signal power P_r is a function of the transmitted signal power P_t . The required received power P_r is given by the SIR at the receiver. The SIR (4) is the ratio between the received signal and the sum of all interfering signals I_i plus the thermal noise N_0 :

$$SIR = \frac{P_r}{N_0 + \sum_{i \in \text{transnodes}} I_i}, \quad (4)$$

where I_i is the signal power from interfering nodes $i \in$ all nodes that transmit concurrently. The SIR is a dynamic parameter which is highly correlated with the detection error rate at the receiver. A receiver has a SIR target level (SIR_{th}), i.e., the SIR needed at the receiver for detecting the transferred information with a certain average error probability. As a result, the reception area borders, in a real system, would not be as sharp as indicated in our simplified model.

It can seem as a higher transmit power P_t , will provide better SIR for a specific transmission, i.e., lower error probability. However, the increased transmit power will also result in a higher level of interference for other concurrent transmissions, i.e., increases the reception (disturbance) area. The interference is a system feedback that can lead to an unstable system, if all stations compensate higher interference level with higher transmit power.

In the following we investigate the properties of energy, interference area, error probability and delay in wireless sensor network. The investigation assume a theoretical network model, based on a regular mesh network. This theoretical model is assumed in order to provide a holistic view of the possible capacity of a wireless sensor network.

A. Energy

To reduce the energy consumption and at the same time reduce the disturbance area a relaying node is placed midway between the source and destination nodes. The transmitted power is adjusted by the power control

mechanism to span a transmitter-receiver distance of $r/2$ instead of r as in the single hop case. For each transmission in the two-hop path the transmitted power P_t required to fulfil the SIR_{th} is $P_t/4$, where P_t is the one hop transmission power. The total transmission power needed for the two-hop path is thus $P_t/4 + P_t/4 = P_t/2$. In the general case, the required transmit power for each individual transmitter through a path with h hops scales as:

$$\frac{P_t}{h^2} \quad (5)$$

if the repeater nodes are positioned at equal distance on a straight line between the nodes. The total power required for all h transmissions throughout the path is thus:

$$P_{tot} = h \frac{P_t}{h^2} = \frac{P_t}{h} \quad (6)$$

This shows that, in terms of energy, it is advantageous to use several relaying nodes between source and destination.

B. Error probability

The message transmission takes place twice in a two-hop path, once at the source node m_i and once at the relaying node m_k . If we assume that the SIR at the receiving nodes m_k and m_j is held at a constant level for guaranteeing a certain QoS over each link, then the error probability P_e is the same over both transmission links. The repeated transmission over adjacent links gives a tree of different permutations of correct or non-correct reception of a bit according to Figure 3. The probability of success P_s and probability of error P_e are mapped in the tree structure.

Figure 3. Error probability permutation tree.

By traversing the tree it is then possible to calculate the probability of successful transmission P_{s_path} over multiple links, which in the two-hop case would be :

$$P_{s_path} = (1 - P_e)(1 - P_e). \quad (7)$$

Equation (7) of course assumes that the bit error probabilities P_e for all hops are non-correlated. This can be argued to be correct since each transmission takes place at different time instances, at different places in space and possibly at different frequencies (different channels). It then follows that the two-hop error probability is:

$$P_{e_{path}} = 1 - P_{s_{path}}. \quad (8)$$

If the error probability is assumed constant, a h hop path will have an aggregated error probability according to:

$$P_{e_{path}} = 1 - (1 - P_e)^h. \quad (9)$$

For a general h hop path, with variable error the path error probability, $P_{e_{path}}$ can be calculated according to:

$$P_{e_{path}} = 1 - \prod_{i=1}^h (1 - P_{e_i}). \quad (10)$$

The conclusion is that the effects of high bit error rates are more profound in a multihop path than in a single hop case, since the error probability is aggregated throughout the path.

C. Interference area

The interfered area at each hop in the two-hop path is one fourth of the interfering area that the single hop transmission creates. Over an h hop path, the area which each individual node contaminates with interference is:

$$h \frac{A}{h^2} = \frac{A}{h}. \quad (11)$$

From this it can be concluded that the multihop topology provides a better spatial capacity (measured in bit/s/Hz/m²) than a single-hop topology (this of course requires a certain density of nodes in order to guarantee connectivity). In principle, all wireless systems can increase their spatial capacity simply by reducing their transmission power, and as a consequence, their range and interference area.

D. Delay

The total delay is trivial; in a two hop path it is $2d$ where the single hop transmission delay is d . The delay

is increased by d_{tr_i} for each relaying node in a path. In the general case the transmissions are repeated h times with the delay d_{tr_i} caused by each transmission and the transmission delay for each hop d_{tr_i} is summed up to the total delay D of the path as:

$$D = \sum_{i=h}^{i=1} d_{tr_i}. \quad (12)$$

If the delay is constant at each node throughout the path and the network works as a store and forward network the total path delay is hd . Here it is assumed that medium access and traffic scheduling do not consume any time.

It should furthermore be noted that the end-to-end delay for a message is dependent on at which protocol level the delay is measured, which forwarding technique is applied, what size the message has and what number of hops are required. If the message is assumed to be very long and is segmented into several small packets that can be transferred concurrently over consecutive hops in a pipelined fashion, the delay imposed by multiple hops is small in comparison to the delay resulting from the link rate and the message size. However, a message of small size which is forwarded in a store and forward manner will experience a delay that is proportional to the number of hops.

E. Loss rate exponent $n > 2$

When the path loss rate exponent n is equal to three the result for total transmitted power over the two-hop path is $P_t/8 + P_t/8 = P_t/4$. This means that the path loss exponent rate n is the dominating factor of the gain of total transmitted power of relaying a message in a multihop path. The total transmission power for the path then scales as:

$$\frac{P_t}{h^2}. \quad (13)$$

In general case, the total transmitted power is:

$$P_t / h^{n-1}, \quad (14)$$

for different n . The total contaminated area in this case is approximately:

$$\frac{A}{h}. \quad (15)$$

The transmission power P_t must still satisfy the SIR_{th} target for the receiver, with a received power of $P_{r_{th}}$.

The total delay D still of course scales as before and the same holds for the error probability.

In conclusion, we can see that the energy and interference area decreases inversely proportional to the number of relaying nodes h , for $n = 2$. These two gains are penalised with delay and error probability. The delay increases linearly with h . The error probability is aggregated throughout a path. The comparison shows that substantial energy gain and spatial capacity gain are possible to achieve by using a multihop topology. Unfortunately, these gains are obtained at the expense of delay and error probability.

The most interesting feature is that when n increases the total power used will decrease as the square of the number of hops h . This compared to the single-hop case where the power instead decreases linearly when n is equal to two, see table 1.

Path loss rate exponent $[n]$	Total power gain	Disturbance area	Total bit error probability	Total delay
2	P_t/h	A/h	$1-(1-Pe)^h$	dh
3	P_t/h^2	A/h	$1-(1-Pe)^h$	dh
4	P_t/h^3	A/h	$1-(1-Pe)^h$	dh
5	P_t/h^4	A/h	$1-(1-Pe)^h$	dh
n	P_t/h^{n-1}	A/h	$1-(1-Pe)^h$	dh

Table 1. Overview of gain and losses in a multihop topology versus a single hop topology.

F. Generalisation of the ideal case

We have assumed that, in a two-hop case, the relaying node m_k was placed exactly midway between the source node m_i and destination node m_j . The perfect placement of the relaying node is not a realistic assumption, however. In the graph in Figure 4 the energy consumption for a single hop transmission is illustrated as a plane. In this example it is assumed that the transmission distance is 100m and the needed power for the one-hop transmission is 0.01 W, (which is indicated by the plane in the graph in figure 4). The total energy consumption for a two-hop path over a relaying node m_k is also plotted (the curved surface). The surface shows the resulting total power when the relaying node is placed at different points in the area between the source node m_i and the destination node m_j . The closed area where the curved surface and the plane intersect show the area where a relaying node must be placed, if any total energy gain should be achieved. In Figure 4 it is assumed that the distance between m_i and m_j is 100 m.

The signal strength at the receiver is assumed to be held at -70 dBm and the path loss $n=2$.

Figure 4. Illustration of power gain for a two-hop versus single-hop transmission for different placements of the relaying nodes.

In the graph it can directly be seen that the largest energy gain is achieved when the relaying node m_k is placed midway on the straight line between m_i and m_j . From the graph it can further be concluded that the density and distribution of the nodes are crucial for the energy and spatial capacity gain in a wireless sensor network.

IV. GEOMETRICAL CAPACITY LIMITATIONS

The capacity in a wireless multi-user communication system (e.g. a cellular system) is often defined as the total bit rate per unit bandwidth per unit area, or bit/s/Hz/m² [19]. In the previous section we have shown that it is possible to increase the spatial capacity to a large extent by using the multihop technique. The spatial capacity is increased by the multihop path if compared with a single-hop transmission. On the other hand, an often forgotten issue when considering a multihop structured network, like a wireless sensor network, is the limit that the flat network topology puts on the achievable capacity and scalability. A lot of overhead is generated for each message when nodes act as relaying stations for messages addressed to nodes further away. In most of the commonly used models for wireless sensor networks, the nodes are randomly distributed over a square plane. Furthermore, the source and destination nodes are randomly chosen out of the total set of nodes. These two assumptions about the wireless sensor network model give rise to an interesting relation between the geometrical size and topology of the network and the overall capacity that the network is able to provide.

A. Capacity of a square area

Let us, as an approximation model of a wireless sensor network, consider the symmetrical mesh network shown in figure 5. We assume that it has x by x nodes and that the nodes are symmetrically distributed to form a regular network topology with a redundancy level of three (as in Figure 1c). We further assume that all nodes have a perfect transmission range of r . The nodes generate data to transmit according to an average message generation intensity $\bar{L}$ and the destination node of each transmission is randomly chosen out of the total set of M nodes in the mesh network.

Let us assume that a slice A_s (the shaded area in Figure 5) is cut out in the middle of the network. Then, with a probability of 0.5, a multihop path from a source node to a destination node passes through the slice A_s .

Figure 5. Perfect distributed nodes in a square area, connected in a hexagonal mesh.

The number of nodes M in the mesh network in Figure 5 is:

$$M = x^2. \quad (16)$$

The number of nodes available for relaying in slice A_s is:

$$M_s = x. \quad (17)$$

If the capacity of each node is equal to a unit, the total capacity of the slice is:

$$C_s = M_s = x. \quad (18)$$

If each node in the area is assumed to generate an average traffic load of $\bar{L}$, the load generated by all the nodes G_t can be expressed as:

$$G_t = \frac{x^2 \bar{L}}{2}, \quad (19)$$

Half of this traffic will have its destination on the other side of the slice A_s . The nodes in the slice A_s must provide enough capacity to transport the traffic $G_t/2$, i.e.,

$$C_s \geq \frac{G_t}{2}. \quad (20)$$

This puts a constraint on the amount of messages $\bar{L}$ that each node is allowed to produce. Using (18) and (19) in (20) gives:

$$x \geq \frac{x^2 \bar{L}}{2}, \quad (21)$$

which further gives that:

$$\bar{L} \geq \frac{2}{x} \text{ or } \bar{L} \geq \frac{2}{\sqrt{M}}. \quad (22)$$

As a result, the nodes in the slice A_s will be congested when the network size grows if the average load $\bar{L}$ generated by each node is constant. This phenomenon is intuitively obvious, when one considers that there exists a difference in dimensions between the number of traffic generating nodes ($M = x^2$) and the size of the most crowded passage ($M_s = x$) in a flat network. Note that we have assumed that source and destination nodes are chosen randomly out of the total set of nodes, i.e., the traffic is not assumed to be local. In next section we provide a model focusing on the relation between the locality of the traffic and the capacity limit.

B. Capacity of a circular area

In order to give the relation between how local the traffic must be and the capacity limitations, an infinite plane with an infinite number of nodes is assumed. The nodes are arranged in an infinite regular hexagonal mesh with a connectivity of six (a redundancy level of three) as shown in Figure 6.

Figure 6. Symmetrically distributed nodes in an infinite plane, connected in a hexagonal mesh.

In the infinite plane in Figure 6, we cut out a circular area A_c , which generates an amount of traffic G_c . Around A_c a circumference border A_b is cut out. The number of nodes within A_c is finite, whereas the number outside the border is infinite. Therefore the probability that the destination node is outside A_b is equal to one. The border A_b must thus have a transport capacity that can take the whole of the generated traffic G_c from inside the circular area A_c to destination nodes in the area outside A_c . The generated amount of traffic G_c is given by the number of nodes M_c inside the A_c area multiplied with the average traffic load $\bar{L}$ generated by each node. If we assume that the radius of A_c is h hops, the number of nodes M_c in A_c is:

$$M_c = \frac{6h(h+1)+2}{2} = 3h(h+1)+1 \quad (23)$$

$$\approx 3h(h+1)$$

The traffic generated inside the circular area is:

$$G_c = \bar{L}M_c \quad (24)$$

The capacity C_b of the circumference border nodes is given by the number M_b of nodes in the ring assuming that each node has unit capacity.

$$M_b = C_b = 6(h+1) \quad (25)$$

The requirement that C_b is greater than G_c thus gives (using (23), (24) and (25)):

$$\frac{3h(h+1)\bar{L}}{6(h+1)} \leq 1. \quad (26)$$

The average load of traffic that each node in the circular area is allowed to generate is then:

$$\bar{L} \leq \frac{2}{h} \approx \frac{1}{h}. \quad (27)$$

It can directly be seen that the capacity decreases very fast when the number of hops increases. The conclusion is that the vast majority of the traffic in a wireless sensor network must be local, if the individual node should be allowed to generate any substantial amount of traffic.

V. CONCLUSION

This paper provides a brief overview of the main capacity and performance issues in a wireless sensor network. It is argued that the fault tolerance and the energy gain achieved in a multihop topology (multiple paths) is its strength compared to single-hop architecture. It is further shown that the energy gain is achieved at the expense of delay and increased error probability. This indicates that a very careful balancing act must be performed between these parameters in order to gain in the global overall performance perspective. It further indicate that fault tolerance must be introduced by the use of multiple paths over which the communication can take place.

The overall spatial capacity is increased as a result of the spatial channel reuse in a multi-hop topology. On the other hand the geometrical topology of the network has also been shown to give rise to capacity limitations. The conclusion is that the capacity of a wireless sensor network does not scale well, when the number of member nodes is increased. If source and destination nodes are randomly chosen out of the total set of nodes, the results clearly shows that information transportation and control information can only be distributed in a very limited range from the source node.

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