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Introduction to wireless networks

1. Preface

This white paper raises some fundamental issues the design engineer should address before deciding upon a communication approach for a wireless network. As no universal wireless network solution exists, it should be custom tailored to suit the application demands.

Defining your application communication characteristics is the key to ensure optimal communication reliability and resistance to interfering noise sources.

2. The network concept

In multiple node applications where one or several nodes need to be able to communicate with all, or a subset of the other nodes in the system, some form of network approach is needed.

A general definition of a network is:

"Any arrangement of elements that are interconnected"

The fundamental purpose of the network realization is simply providing a defined procedure of interconnection and information flow between nodes. Secondary issues are ensuring the necessary communication reliability in order to obtain satisfactory application functionality.

Typical network scenarios are:

- The nodes in a system are scattered to such an extent that the nodes are not within radio range of all the other nodes in the system.

  Example: Consider an industrial sensor application where the nodes are positioned at various locations in a large building. All sensor nodes report status to the master control node at predestined time intervals, or if the measured value exceeds given alarm thresholds.
  If a sensor node is outside radio range of the master control node, the information must be relayed to the master control node by means of networking. This is achieved by other sensor nodes located between the two nodes retransmitting packages not addressed to themselves.

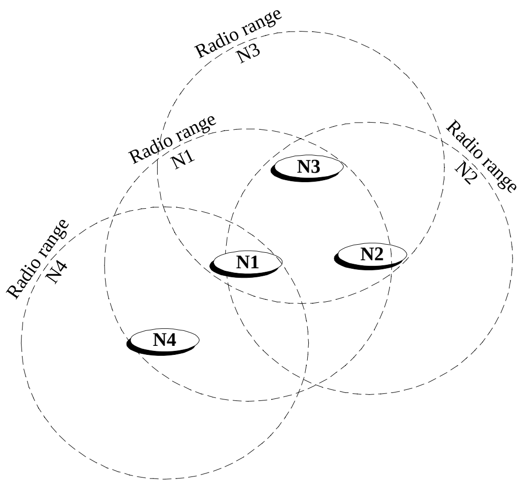

Figure 1 - Non overlapping radio ranges

- Systems where the inherent mobility of nodes, transfer nodes in and out of radio range of other nodes in the system.

  Example: Consider a system consisting of nodes attached to mobile personnel working at a location larger than the radio range. In order to exchange information between any two nodes, retransmission of some packages is likely. As nodes are considered mobile, the available nodes capable of relaying the package to the correct recipient are changing over time.

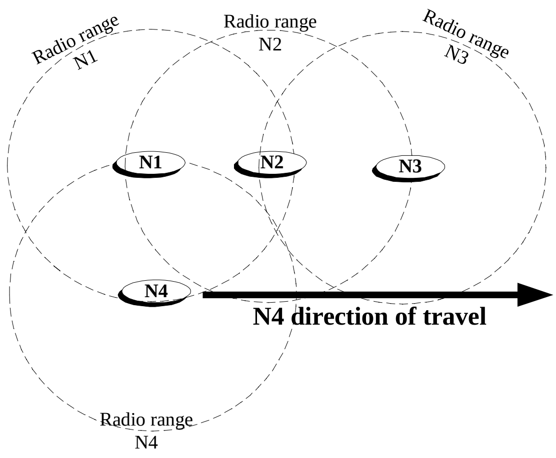

Figure 2 - Time varying radio range overlap

- Systems where it is natural to divide the system nodes into groups. A center node in a group may communicate and exchange status information with center nodes in other groups.

  Example: Consider a system with multiple nodes grouped at separate locations. This might be sensors in an alarm system with multiple sectors. In this case it might be natural that the nodes report their status to a sector master node. In case of sector alarm, the sector master node transmits an alarm status message to the alarm master node.

3. Network approaches

3.1. Star network

Perhaps the easiest network approach is the star topology illustrated in Figure 3.
All communication is directed via the central node, which retransmits the information to the destination node. The central node acts as a relay station and must therefore be positioned within radio range of all nodes in the network. Theoretically, radio range of the network nodes may be as much as doubled.

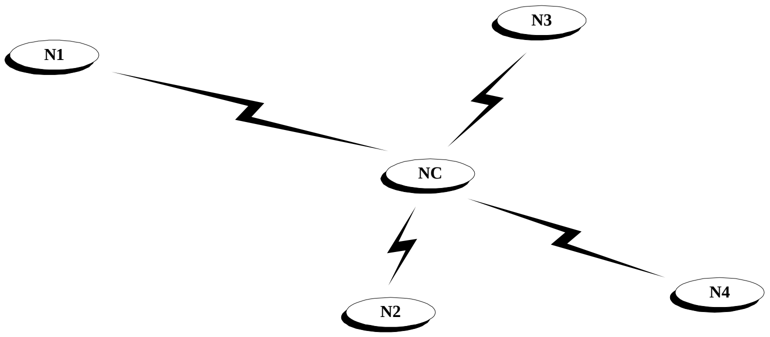

Figure 3 - Star network principle

Below is described a basic network scenario where node N4 needs to transmit information to node N1.

The course of action is as follows;

- N4 needs to alert N1
- N4 generates and transmits a package to node NC, requesting acknowledgement
- Nodes N2 and N3 ignore the package as they are not the designated recipients
- NC recognizes itself as recipient and transmits an acknowledgement package addressed to node N4
- Nodes N1, N2 and N3 ignore the package as they are not the designated recipients
- N4 recognizes itself as recipient of the acknowledge package from NC, ending the communication with N1
- NC retransmits the package to N1 without delay (provided there is no other channel traffic)
- N1 recognizes itself as recipient of the retransmitted package and transmits an acknowledgement package addressed to node NC
- Nodes N2 and N3 ignore the package as they are not the designated recipients
- NC recognizes itself as recipient of the acknowledge package from N1, ending communication

In total, 4 packages are sent in order to achieve a successful acknowledgement of a transmitted package. In a point-to-point system (assuming the nodes are within radio range of each other), only two packages are generated.

The obvious bottleneck of the system is the communication capacity of the center node. The communication intensity of the network must therefore not exceed the maximum throughput of the center node.

An advantage of using a single node to control all traffic, is that the system communication delay is kept at a minimum. The center node may retransmit any package without delay, as long as no other traffic occupies the operating frequency. The system delay issue described in Chapter 4.7 is therefore not applicable for this network approach.

The use of this topology is limited to applications where the node positions are fixed or where node mobility is limited. The placement of the center node is dictated by the application environment and node distribution. As the center node is performing the 'lionsshare' of the work, it is often desirable that it is a stationary mains-fed unit so that the current consumption is no longer an issue.

3.2. Single retransmission of received packages

A simple network approach is that all nodes are to retransmit received packages not addressed to themselves once. The link layer makes sure that previously received packages are identified, avoiding infinite retransmissions. This necessitates a memory function where recently received package identity information is stored.

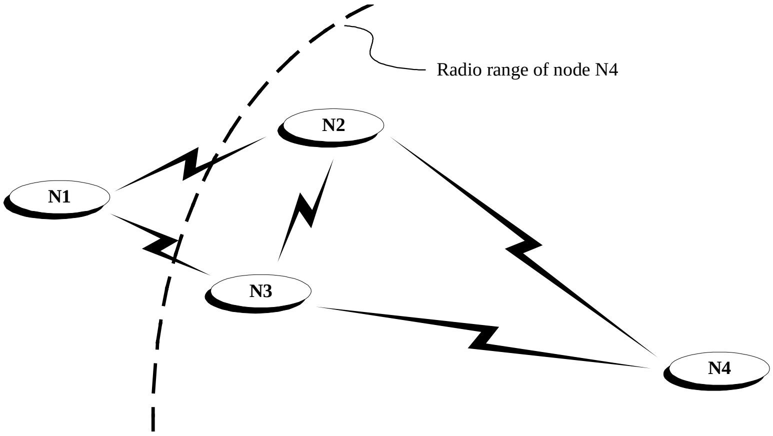

Figure 4 - Basic network communication scenario

Figure 4 illustrates a basic network scenario where node N4 needs to transmit information to node N1 outside radio range.

The course of action is as follows;

- N4 needs to alert N1
- N4 generates and transmits a package to node N1, requesting acknowledgement
- The nodes N2 and N3 are the only recipients, as N1 is outside radio range of N4
- N2 and N3 identify the recipient address to be another node
- N2 and N3 retransmits the package at a random time instant, remembering the package ID to prevent multiple retransmissions
- N4 receives the retransmitted package and discards it as a retransmitted version of it's original transmitted package
- N1 receives a retransmitted package from N2 or N3 (depending on which of the two nodes that retransmitted the package first)
- N1 recognizes itself as recipient and transmits an acknowledgement package addressed to node N4
- N1 receives the second retransmitted package from N2 or N3, and ignores it as already being processed
- The nodes N2 and N3 are the only recipients of the acknowledge package from N4, as N1 is outside radio range of N4
- N2 and N3 identify recipient address to be another node
- N2 and N3 retransmits the acknowledge package to node N4 at a random time instant
- N1 receives the retransmitted acknowledge package and discards it as a copy of the recently transmitted package
- N4 receives a retransmitted acknowledge package from N2 or N3 (depending on which of the two nodes that retransmitted the package first)
- N4 recognizes itself as recipient of the acknowledge package, ending the communication with N1
- N4 receives the second retransmitted acknowledgement package and discards it as a copy of the previously received package

In total, 6 packages are sent in order to achieve a successful acknowledgement of a transmitted package. Using the single dedicated relay node as described in the star network chapter, would in turn generate 4 packages.
A network inevitability introduces more traffic than a point-to-point system. The network strategy described is based on the principle that all received packages are retransmitted once unless the receiving node is the recipient.

Assuming all the nodes in the network are within radio range of each other, the total number of packages generated for a simple package transmission with acknowledge is N+N-2. N is the number of nodes in the system.

The timeslot in which retransmission is to take place, must be long enough to allow all nodes to retransmit any received package in order to avoid collision. *System response time is hence proportional to the number of nodes in the system* (see Chapter 4.7).
As can be seen from Figure 7; in order to avoid blocking or traffic jamming, the average package rate (initiated by a node and not by retransmission), must be less than 1/[retransmission timeslot].

This simple networking approach is suitable for systems where a limited number of nodes coexist within the radio-range of any given node, resulting in a limited system delay/response time. The approach is also robust against individual movement of network nodes.

3.3. Mapping of gateways through neighboring nodes

A more bandwidth efficient, but also more complex approach is illustrated in Figure 5. This solution is based on the assumption that the nodes have the ability to 'learn' the existence of the other nodes in the system, and not only the nodes being within its own radio range. This information is stored in a table, which is updated immediately as the network is established, and when communication is lost between two nodes during normal operation.
The table has the following principal organization and information content:

Active nodes in the application network	**Which node within radio range is the gateway to the network node in the left column**
1	X
2	Y
...	...
N	Z

Two different package types are used in the network;

- Network mapping packages
- Application communication packages

When a network mapping package is sent, all nodes intercepting the package answers with its address and a list of nodes of which it is able to communicate with. This enables the node to build a table where gateways to nodes outside radio range can be identified. If two nodes both provide a gateway to the same distant node, the first network mapping package received decides the gateway node.
The mapping sequence involves sharing information of the network topology by asking: "Who can hear me, and who can you communicate with?"

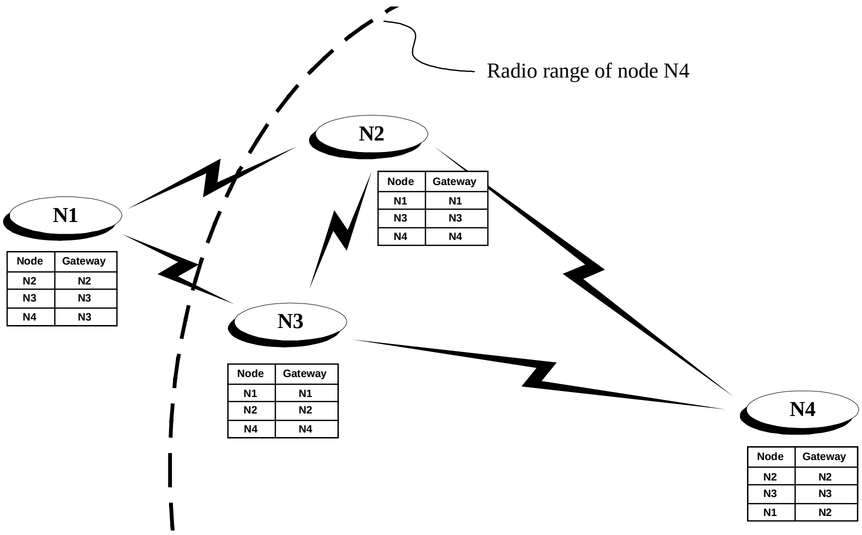

Figure 5 - Network mapping of neighboring nodes reducing retransmission traffic

When a node transmits a package to a dedicated node, the node has two options; either sending the package directly to the recipient (if it is within radio range) or via a gateway node. If the recipient node is within range, network traffic is limited to only two packages; the information package, and the resulting acknowledge package from the recipient.

If the package has to pass through a gateway node, the number of packages is doubled. Normal procedure is that the gateway node sends an acknowledgement package to the package originator, taking over the responsibility of the transmission. The gateway node then transmits the package to the recipient (or via another gateway node) closing the transmission upon reception of an acknowledgement package.

If a recipient node has moved out of range, or is obscured by a noise source, the package transmission chain is broken. If a node fails to receive an acknowledge package within a predefined time period, it initiates the mapping procedure in order to rebuild a valid communication table. This enables the establishment of an alternative package transmission path through the network. For a relatively stable network, mapping traffic is significantly lower than the normal communication traffic.

Note that as the communication path is known at transmission, system response time is kept at a minimum, as opposed to the network approach described in Chapter 3.2.

The course of action is as follows;

Network topology mapping-sequence (performed by all nodes);

- Node N transmits a network mapping package asking: "Who can hear me, and who can you communicate with?"
- All nodes receiving the package responds with a 'I can hear you, and I can communicate with nodes; X, Y, Z ...'-package
- Node N updates the network gateway table
- Sequence is repeated until the content of all tables is stable

Communication sequence;

- N4 needs to alert N1
- N4 checks its network communication table and finds that N2 is the gateway to N1
- N4 generates and transmits a package to node N2 (with final designator address N1), requesting acknowledgement
- N3 ignores the package as it is not a recipient or a gateway node
- N2 receives the package and finds that the designated recipient is N1
- N2 sends an acknowledgement package to N4
- N2 checks its network communication table and finds that N1 is within its radio range
- N4 receives the acknowledge package from N2, closing the transmission as N2 has taken over responsibility of the transmission
- N2 relays the package to the final recipient, N1
- N1 receives the package and transmits an acknowledgement package addressed to node N2
- N2 receives the acknowledge package, ending communication with N1

In total 4 packages are sent in addition to the packages generated in the network mapping sequence, where 8 is the absolute minimum number of network mapping packages. The total number is depending on the node communication order and may vary.

4. Parameters to consider in a networking application

Numerous networking approaches exist and most are custom tailored to a given application or system. It is useful to define some fundamental characteristics of the application before deciding upon a network solution. *Keeping the complexity as low as possible without compromising the application functionality* is the primary design challenge.

The following aspects of the application should be considered and defined:

4.1. Total number of nodes in the system

The number of system has to be seen in conjunction with the application communication activity. A high number of nodes within radio range of each other will cause significant traffic if a simple retransmission strategy is to be used. Lets assume a package size of 100 bits and a datarate of 100Kbit/sec. The duration of a package is then 1ms. Assuming 100 nodes are within radio range, retransmission will cause 99 packages to be transmitted, resulting in 100ms of transmission time for a single package. As the system is not synchronous, guard-time needed to avoid collisions must be added (See Figure 8).
For systems with low communication activity, this is generally not a problem, but as the information flow increase, the network may soon be jammed due to retransmitted packages.

4.2. Network traffic intensity

The retransmission approach must be used with care in systems with high communication intensity. Unnecessary traffic generated by the network may jam the application as a result. Key information is how often nodes within range of each other is active (TX) and the duration of each subsequent package. This is decided by the application and most often involves statistical considerations.

In cases where a large amount of data is to be transferred, the network may be designed to process data transfer on different frequencies. By organizing communication this way, the network is still operational even during lengthy data transmissions. The nodes first establish contact on the signaling channel, then shifting the communication to an available traffic channel.

4.3. Geographical distribution of nodes

In systems where the distance between nodes is small compared to the radio-range of the radio transceiver, a more elaborate network approach is needed in order to minimize traffic resulting from retransmissions. If the number of nodes is large, both described methods generate unnecessary traffic, as a high number of retransmissions within a limited area are superfluous.

4.4. Inherent mobility of nodes

Where nodes are to be mobile after initial installation of the system, they might move out of radio range of some nodes, whilst moving into radio range of others. If a minimum traffic network approach (as described in Chapter 3) is to be used, the system nodes must update the *nodes-within-range*-table at constant intervals. This will in turn introduce extra traffic load and should be taken into consideration.

4.5. Application node hierarchy

Where it is natural to divide the system nodes into subgroups, the network solution may be designed to inhibit inter-group communication except at key node level as shown in Figure 6 below.

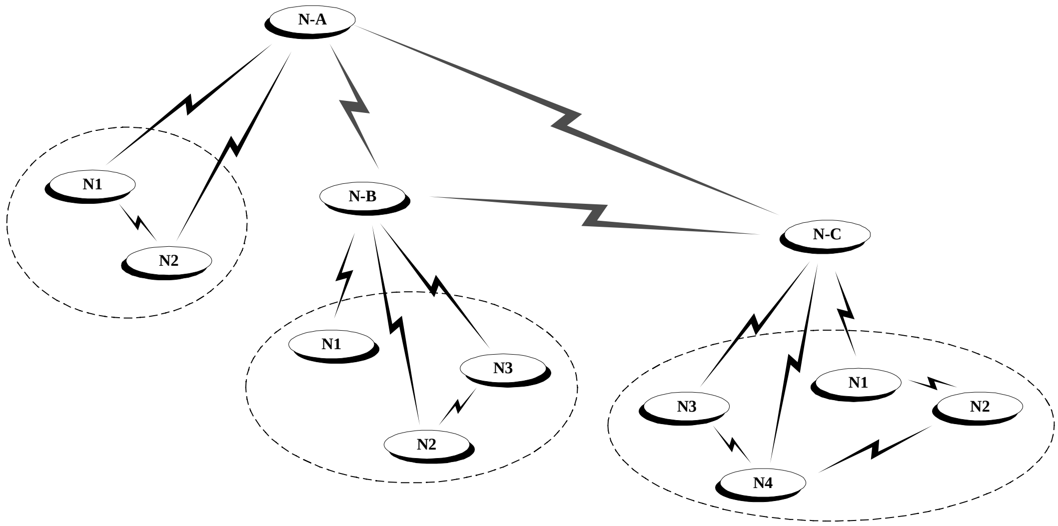

Figure 6 - Hierarchy organized network

4.6. Communication reliability requirement

The communication reliability, often referred to as *Quality of service* (QoS), must be defined for the application. In this context, the question is; what information loss can be tolerated whilst still achieving satisfactory operation?

For systems depending on file transfer, the answer is *none*; every package sent must be received in order for the application to work. The network approach must therefore be based on repetitive package transmissions until an acknowledge-package from the recipient is received.

For a sensor system, one may normally accept the loss of a larger amount of packages when the application is repeating sensor information at regular intervals.

4.7. System response time

An important parameter is the system response time required. In this context: "What is the maximum time between a package is received before it may be retransmitted?"

Consider the imaginary network shown in the figure below.

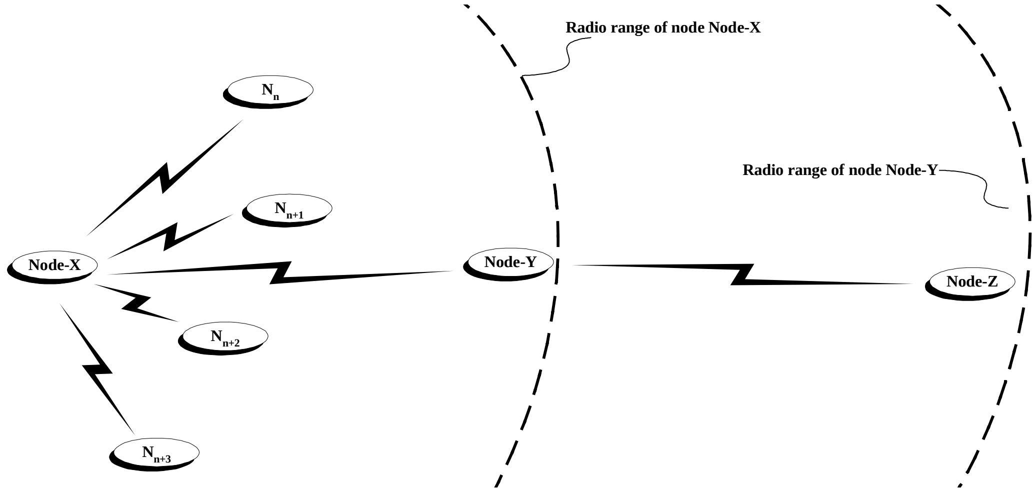

Figure 7 - Network example; System response delay due to retransmission

Node X on the extreme left transmits a package to the node on the extreme right, Node Z. These two nodes are assumed to be out of radio range of each other. Also; the only node within range of Node Z, is Node Y. The message must therefore be relayed through Node Y. For the retransmission approach described in Chapter 3.1, the transmission procedure is sketched in Figure 8. Note that that retransmission is performed at a random time instant to avoid collisions. Worst case package delay is governed by the defined retransmission period, t_{reTX}. This is a system parameter proportional to the number of nodes expected to be within range of each other.

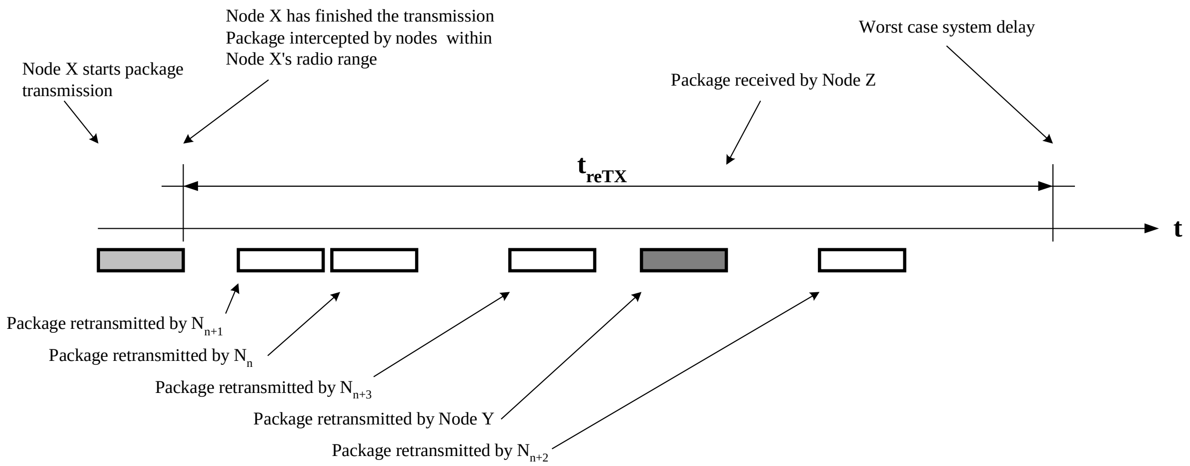

Figure 8 - Network example; System response delay due to retransmission

For the network approach described in Chapter 3.3, this is not an issue as the relay node retransmits the message immediately after reception.

4.8. Presence of noise or potential jammers in the field of operation

It is important to comprehend that the power density of the signal transmitted from any system node, as well as noise sources, decrease with 1/range^2. Presence of noise is thus *generally not a problem if the noise power density at the receiving node is less than the power density of the incoming package at the same location*.

Typical noise sources are other systems operating in the same frequency band. A networking approach generally enhances overall system noise rejection as other nodes provide alternative communication paths between nodes, both geographically and in the time domain. Figure 9 illustrates the general principle.

Assume a noise source is positioned at a certain location:
If Node 1 sends a package to Node 2 during a period when the noise source is active (t=1), two scenarios are likely when the direct transmission path is lost due to interference:

A: Node 2, being positioned outside the noise source interference range, intercepts the package and retransmits it via Node 3, reaching Node 4.

B: The package is intercepted by Node 2 at t=1, and then retransmitted at time instant t=2 when the noise source is silent.

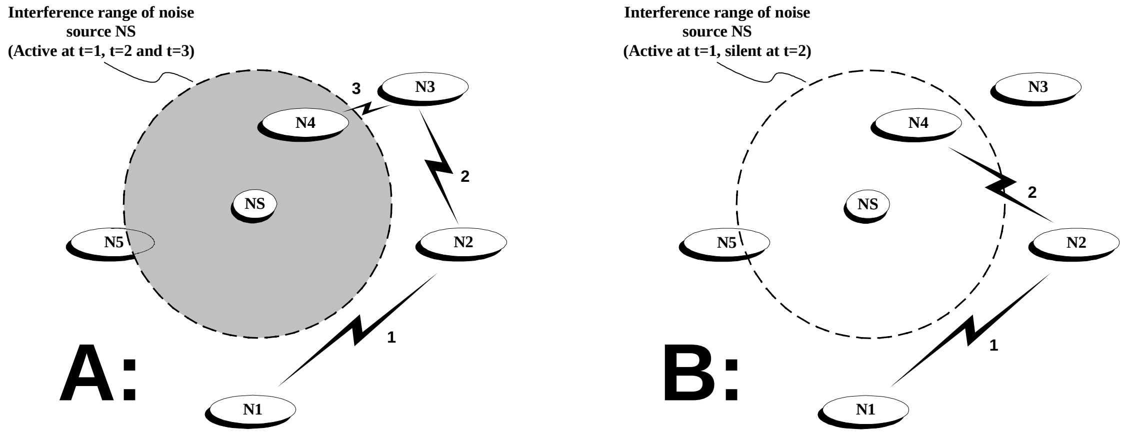

Figure 9 - Alternative package propagation paths in the presence of noise

It is important to be aware of the fact that interference is likely in certain environments, but mostly only for short periods of time. The key questions are:

- What are the likely interference sources?
  (other ISM applications, parallel networks etc.)
- What is the probability of interference over time?
  (ISM applications are almost always active for only a short time)
- How will temporary jamming affect the application?
- How may the system communication protocol be designed so that temporary jamming does not affect application functionality?

5. Summary

"There is more than one way to skin a cat...". The same applies to network implementation. As communication networks are almost always custom tailored to a specific application, there is no "all purpose" network solution. The key to efficient communication and Quality of service is to fully understand the dynamics of your application communication requirements. Define your application requirements and characteristics in terms of;

- maximum response time
- maximum number of system nodes
- package loss tolerance
- network peak traffic (packages/sec or bits/sec)
- node mobility behaviour
- application operation area infrastructure (attenuation, mains availability etc.)
- definition of probable interference scenarios

Once defined, the network solution capable of meeting your specifications may be chosen.

The characteristics of the examples described in Chapter 3 are listed in Table 1.

	Star network	**Retransmission**	**Gateway mapping**
Maximum radio range increase	2 · node radio range	(N*-1) · node radio range	(N*-1) · node radio range
System communication delay	Low	High	Low
Complexity	Low	Medium	High
Node mobility	Low	High	High
Communicaton efficiency	Medium	Low/Medium**	High/Medium**

*: N is the number of nodes in the system
**: Depending on the number of nodes in the system

Table 1 - Network examples, summary of characteristics

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