Communication issues in Large Scale Wireless Ad hoc Networks

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Abstract

Ad-hoc networks are networks that are formed automatically without any pre-existing infrastructure. These networks may consist of various types of mobile devices – such as PDAs, laptops, cell phones and other mobile computing devices. Each node in a wireless ad hoc network performs computational tasks as well as communication routing. Without the existence of dedicated routing devices, the nodes relay traffic to each other to extend their communication range. This paper gives an overview on the current technologies – intelligent agent systems – and their implications to solve common problems in ad hoc networks. We will also introduce our current research directions, and provide a promising analysis to achieve efficient transmissions in a large-scale ad hoc network using multiple channels, an option, which is already in the MAC layer of IEEE 802.11. We will show also that in noisy environments latency reduction in multi-hops is significant to single hop networks even for greater number of relay nodes. The approach described in this paper could be use to develop efficient large-scale ad hoc networks.

1. Introduction

Wireless networks have become very popular recently because of their ability to allow users to access network services without having to be stationary and plugged in. The success of mobile phones suggests that wireless networks are soon to follow suit, with many people now owning laptops and PDAs both for work and play on the move.

Most wireless networks, like mobile phone networks require an infrastructure in place that is both costly and time-consuming to implement. The emergence of multi-hop ad hoc wireless networks allows us to network a group of geographically distributed nodes without the requirement for fixed routers. This is achieved by each individual node acting as a router [1] by forwarding packets on request received from neighbours within its transmission range. This allows nodes that are not in radio contact to communicate by passing data through intermediate nodes, thus allowing communication over distances far greater than that of the nodes' radio transceivers. Initial applications of ad hoc networks have mainly been in military applications, disaster communication and sensor networks; however, the consumer market is becoming more and more interested in this technology as we strive towards ubiquitous computing.

This paper continues our research into ad-hoc networks and the investigation of the feasibility of large-scale ad-hoc networks [2]. The next few sections will investigate the advantages of multi-hop networks for data transfer over that of a single hop. In a single hop scenario both nodes will have to radiate more power to propagate the data the same distance, and as a result suffer more from the radio propagation and contention issues that limit bandwidth. In a multi-hop scenario nodes use lower power radios, reducing the likely hood of radio propagation issues and collisions with other nodes. We prove in this paper that up to a certain limit of hops, multi-hop networks can provide higher throughput and hence reduce the delay in data transfer when compared with a single hop of the same distance.

Section 2 will talk about the importance of mobile agent technology [3] and its promising use in ad hoc networks; in section 3 and 4, we will analyse the power and latencies of multi-hop networks and compare the results with single hop networks. Section 6 describes the general research undertaken by our research team at Portsmouth University, and finally in section 7 we conclude the paper by highlighting important results and directions.

2. Multi-Agent Systems in ad hoc networks

Mobile agent systems are a new technology based on mobile code that can migrate from one node to another in order to collect, analyse and make decisions locally or remotely. Mobile agent technology can offer a new concept for communication over heterogeneous network topologies. A number of advantages of using mobile agents have been proposed and identified. These advantages include: overcoming network latency, reducing network load, executing asynchronously and autonomously, adapting dynamically, operating in heterogeneous environments, and having robust behaviour [4]. Furthermore, agent based approaches for information management and transmission routing have been evaluated in [5-7]. However, most of them focus on the distribution in static networks.

Mobile agents are very efficient and well organized in large-scale dynamic networks. The information that has been collected from the domain by agents could be used as a knowledge base; subsequently the agents can take some intelligent decisions. Furthermore, this information that reflects the past and present network behaviour could be analysed and manipulated to predict network behaviour in the future. In the next sections we will consider the issues of power and latency in large-scale ad hoc networks, as it is vital to move code as agents or packets as messages.

3. Power issues in large sale ad hoc networks

In ad hoc networks nodes consume power for both processing tasks and transmission routing, even in the absence of any immediate communication To make the matters worse, nodes consume more power to overcome free space loss, and signal dispersions as it emerges with longer distances, especially with large-scale networks. The power consumption is certainly a major issue in such environments. We will show in this section that large-scale multi hop ad-hoc networks conserve more energy than single hops.

A signal transmitted by a node with power P_t would propagate over a distance D, yielding a power of P_r at the receiver. To extract the correct information from the signal, at a given level of noise, the network card of the receiver should tolerate a minimum receiving power of at least P_r. One would express the power loss as

$$\frac{Pt}{\mathrm{Pr}} = \frac{(4\pi fD)^{\alpha}}{C^{\alpha}} \quad (1)$$

where f and C represent the frequency of the signal and the speed of light respectively. In theory, α is equal to 2, but for realistic environments α is equal to 3.5 or 4. In multi-hop ad-hoc networks, with a pipeline of n nodes, the distance D would be divided into n-1 equal hops, for simplicity, with the power being regenerated at each relay node yielding a received power of

$$\frac{Pt}{\mathrm{Pr}} = \frac{(4\pi fD/(n-1))^{\alpha}}{C^{\alpha}} \quad (2)$$

Thus the overall end-to-end conserved power, C_p, in a multi-hop over a single hop ad hoc network would be obtained by dividing equation (1) over (2) and averaging over n-1 links; see figure 1.

$$Cp = (n-1)^{\alpha-1} \quad (3)$$

For a larger-scale multi-hop pipeline, considerable energy is saved over a single hop. There is a great benefit in controlling power over short-range transmissions, which can also reduce the total level of interference in homogeneous multi-hop ad-hoc networks under fixed traffic conditions. It has been stated [8] that the level of interference can itself be reduced by the same amount as the transmitted power. Obviously this equation does not take into consideration retransmissions, fading and uneven ranges between network cells.

Due to short-range transmissions, the power consumption in a multi-hop ad-hoc network can be reduced; refer to figure 1. The major benefit from controlling the power in short-range transmissions is that the level of interference can diminish too, as shown in the next equations.

4. Latency in multi-hop and single hop ad-hoc networks

End-to-end delay in a multi-hop network depends on several factors: length of the frame transmitted, routing deployed, connectivity, link capacity, acknowledgment policies, and retransmissions. The latency increases as the frame travels over several hops. Fortunately, when applying fragmentations to longer frames, concurrent transmissions can improve the end-to-end delay considerably. In store-and-forward transmission, a node stores a frame, replies to it with an acknowledgment – depending on the scheme used – and forwards it to the next node on the routing path. In wireless networks, to improve the reliability, acknowledgements are requested for every fragment sent. Thus acknowledgement policies bring single and multi-hops wireless ad-hoc networks to the same level of overheads, as we will show later. Furthermore, the delay in multi-hop scenarios is compensated for in part by a decrease in link capacity of a single hop, as interferences are more severe in single hop and therefore, the link capacity diminishes. Using Shannon's theorem, with E being the signal to interference ratio, B the bandwidth, and N the number of nodes in a routing path of an ad hoc network – using equation 3, we can express the link capacity [5], assuming that the interference compensated for by the multi-hopping, as

$$C_{link\,=}\ B \log (1 + (n-1)^{\alpha-1} E) \quad (4)$$

We can now write the ratio of the latency of a single hop to a multi-hop as

$$\frac{T_s}{T_m} = \frac{L_s / C_s}{L_m / C_{\ m}} \quad (5)$$

Using equation 4 and some approximations, we can express the link capacity for single and multi-hop schemes as

$$C_m / C_s = 1 + (\alpha - 1) * \ln(n-1) / \ln(E) \quad (6)$$

The transmission length in bits, in a single hop wireless network, ignoring the inter-frame spacing, with fragmentations and acknowledgments can be expressed as shown below where L is the data frame, A is the acknowledgement and F is the fragment size in bits.

$$Ls = L + \frac{L * A}{F} \quad (7)$$

We will consider in this analysis two approaches for a multi-hop chain: one that uses the single channel over the whole communication exercise and the second one that uses the multi channel transmissions with the node being able to switch between different channels to avoid collisions with others. We will prove under the results of equation 6 that the multi channel transmission over a linear chain, under a lightly loaded network offers lower latency up to certain number of relay nodes than a single hop. In both cases, we assume that

CSMA/CA with DCF is deployed within the MAC wireless protocol IEEE 802.11. The analysis takes into consideration a hop-by-hop acknowledgment along the routing path discovered by an ad hoc algorithm such as AODV.

In multi-hop ad hoc networks, frames travel along a chain of relay nodes toward the destination. Due to the broadcasting nature of the communications, nodes within range of each other interfere, and hence diminish the amount of concurrency in the transmission. As shown in figure 2, a transmission from the node 1 can be affected by a simultaneous transmission from node 2. The reception at the node 2 from node 1 can also be affected by a possible transmission from node 3. Even worse, interferences from node 4 may go way beyond its communication range affecting the reception at node 2, hence preventing node 1 from transmitting successfully to node 2.

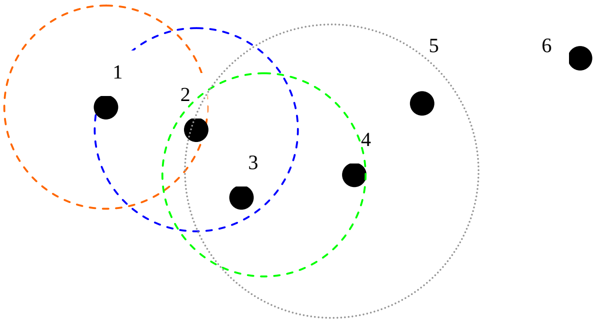

Figure 2: Interference range in a chain of ad hoc nodes

Assuming that a transmission will start from node 1 towards node 6, using a single channel transmission. It would take (n-2)*(F+A) for the first fragment to reach the node n-1, followed by successful L/F fragments and acknowledgements giving a length of L + L/F*A bits. Finally, due to the interferences from possible node 2, 3 and 4, node 1 schedules its back off time to add **b** number of gaps between each fragment to allow nodes in the chain to transmit without interfering. Each gap is of length (F+A). There will be as many gaps as there are fragments yielding to (b-1)*(L/F-1)*(F+A). After some mathematical simplifications and manipulations we end up with the following total transmission bits.

$$Lm = (n-(1+b))(F+A) + aL(1+\frac{A}{F}) \quad (8)$$

In this equation b=2 represents only the node 2 affecting the transmission of node 1. This is unlikely to represent the real situation. Whereas b=3 represents, in addition to the node 2 colliding with node 1, node 3 affecting node 2 from correctly hearing any transmissions from node 1. The maximum channel utilization under this assumption is 1/3 - refer to equation 8. In paper [6] similar results have been reported. However, under the influence of hop interferences, we will show that the throughput as compared to a single hop can be improved slightly. Finally, for b=4, which is probably the most real case, in addition to nodes 2 and 3 interference, node 4 can also affect the reception at node 2. This will lower the channel utilization to ¼, as reported in [9]. Finally the ratio of the latency of a single hop to a multi-hop, using equations 6, 7 and 8 can be expressed as

$$R_l = (1+(\alpha-1)*\ln(n-1)/\ln(E))/(b+(n-(1+b)F/L) \quad (9)$$

As shown in figure 3, in a non-noisy environment, the latency increases with the number of hops, and it is worse with interference from node 4. However, due to the power issues and environment interferences, the single hop seems to loose link capacity, where as the latency in multi-hop scenarios is compensated for by individual link capacity increases such that O(ln (n)). Obviously, when the power is limited it is impossible to reach destination nodes that would have been reached in multi-hop scenarios with the expense of an increase in the end-to-end delay. Furthermore, in very noisy environments, it is very apparent from figure 4 that multi-hop networks perform even better compared to a single hop. Around 128 nodes, the latency in the single hop is about 3.5 times greater than a multi-hop network.

With multiple channel switching, as shown in figure 5, we assume that every node transmits packets received from the application with the carrier f_0. Any frame received from the network with a carrier f_i requiring further routing will be forwarded with the carrier (f_i +1)%a. We also assume the extreme case where interference goes beyond the communication scope of node 4 will corrupt the transmissions from node 1.

The transmission length in bits in a multiple hop wireless network, ignoring the inter-frame spacing, with fragmentations and hop-to-hop acknowledgments can be expanded into the first fragment reaching the n-1 node after (n-2)*(F+A). Although A can be sent concurrently with a transmission from node 2, we will include it here to generalise the equations, the consecutive fragments adding up to L and L/F*A including acknowledgments at the node n, and the remaining gaps result from absence of concurrent transmissions which are a factor of the number of carriers deployed at each node most likely to cause interference with node 1, a*(L/aF –1)*(F+A). Putting all these terms together we can deduce the total transmission in bits to be

$$Lm = (n-2-a)(F+A) + 2L + 2\frac{LA}{F} \quad (10)$$

With a=2, the node uses a dual-channel radio, with each applying alternative frequencies between receiving and forwarding disciplines. In this case without the effect of external interference only node 3 interferes with node 1 at node 2 and the maximum throughput achievable is ½. With a=3, the node uses three alternating channels, in this case node 4 outside its communication range interferes with node 2 while receiving from node 1. With a=4, all nodes in the critical path of the interference will use different channels hence removing any potential collisions. In this case there will be no gaps between the fragments, meaning that the factor a*(L/aF –1)*(F+A) is zero. Extracting the latter from equation 10 yields the following.

$$Lm = (n-2)(F+A) + L + \frac{LA}{F} \quad (11)$$

The ratio, R_l, of a single to multi hop latency can be deduced, in the same manner as in equation 9. The results in figures 6 show that as expected from the equations that the dual and three channel approaches are identical, this is due to the interference caused by node 3 or node 4 on the reception at node 2. Fortunately, a multi-hop scenario with 4 channels provides better latency than single networks for a wide range of relay nodes well over 256 nodes. The latency is compensated for by the individual link capacity increases. In about 64 relay nodes, the latency in a multi-hop network is about 2.5 times less than in a single hop. These results are quite promising for establishing a large-scale ad hoc network. Furthermore, in noisy environments, multi-hop outperforms single hops even switching between fewer channels – refer to figure 7.

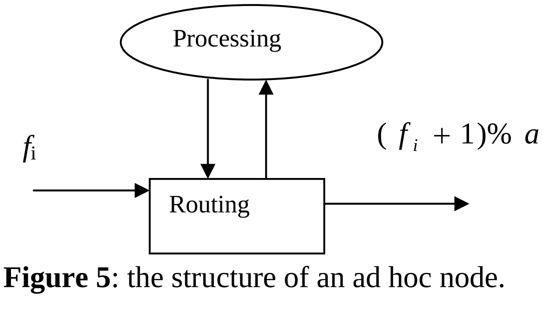

Figure 5: the structure of an ad hoc node.

5. Directions

The University of Portsmouth has a very vibrant research culture producing high quality research in all areas. In the Computer Science department we are particularly interested in several areas of wireless networks to which we outline below.

We are interested in looking into the feasibility of large-scale ad-hoc networks. We feel these are important as it allows the consumers to construct with minimal effort their own wireless infrastructure. This provides fault tolerance and a self-upgrading network as users inevitably update their mobile phones and PDAs. The benefit of this is that no company controls the network and hence there are no connection charges, and the hardware updates itself as time passes with no cost to a single organisation. Particularly we are interested in conducting work to test the feasibility of such a network and the most effective means of operating one.

Included is research into harsh environments, where a wireless data medium suffers significantly from external factors. One example of such an environment would be a research centre specializing in new ways of energy production, where the techniques utilised might prohibit the use of wireless technologies due to interference together with various other propagation issues because of the unique harshness of such environments. In particular we will be looking at ways of mitigating the effects of such interference and providing a wireless network in spite of these factors

The department encompasses research into management of faults such as router and server failures. This field also incorporates congestion in the network and solving such issues by the rerouting of certain traffic. Our group will be looking at new and novel ways of approaching not just traditional fault management but also applying it to wireless networks. Particular areas of interest include the previously discussed large-area wireless networks as one can envisage many problems in such networks, such as node failures and congestion hotspots.

6. Conclusion

In this paper, we have described the direction of our research in the domain of ah hoc networks. We have analysed the power requirement and latency in multi-hop large-scale ad hoc networks. Our analysis suggests that using multi-hop chains as opposed to a single hop saves more power specifically for larger networks, as the power of a signal gets regenerated at each hop, and thus the signal overcomes the interferences induced by the environment. We have shown that the individual link capacity increases for multi-hop with n by an order of ln(n) and thus the end-to-end delay is compensated for up to a noticeable number of relay nodes. These results suggest that with some traffic patterns, locality of traffic and noisy environments multi-hop ad-hoc networks will perhaps be a favourable candidate to support general-purpose communications, and interact with the Internet to form solid communication environments.

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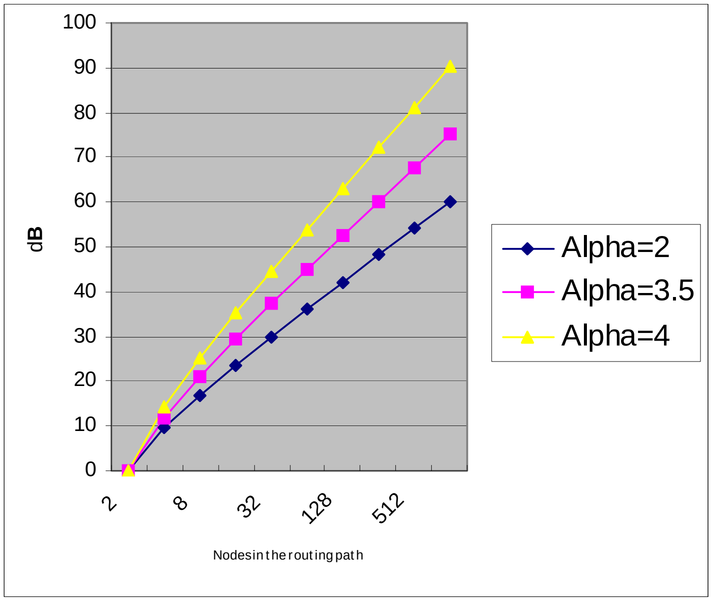

Figure 1: Power conservation in multi hop over single hop ad hoc networks.

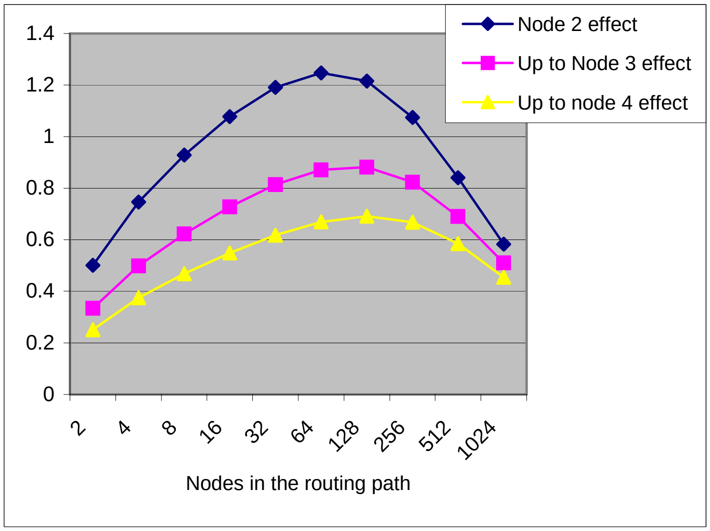

Figure 3: Ratio of the latency of a single hop to multi-hop ad hoc network with hop interferences, with high signal to noise ratio 251, with α = 3.5 and packet lengths 200 times longer than the fragments.

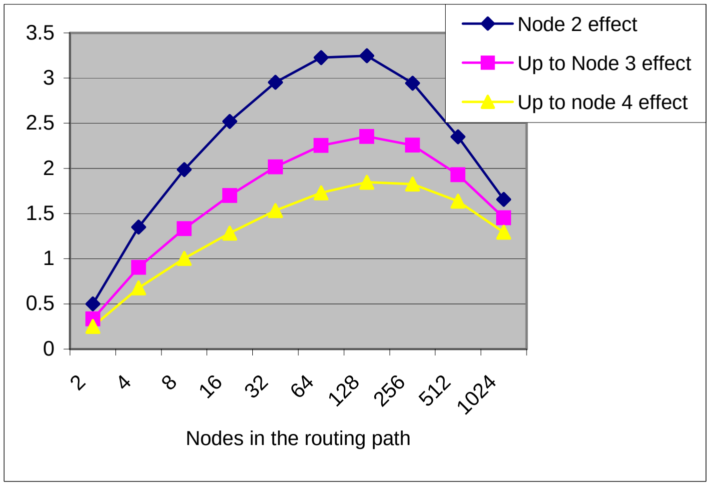

Figure 4: Ratio of the latency of a single hop to multi-hop ad hoc network with hop interferences, with low signal to noise ratio of 5, with α = 3.5 and packet lengths 200 times longer than the fragments.

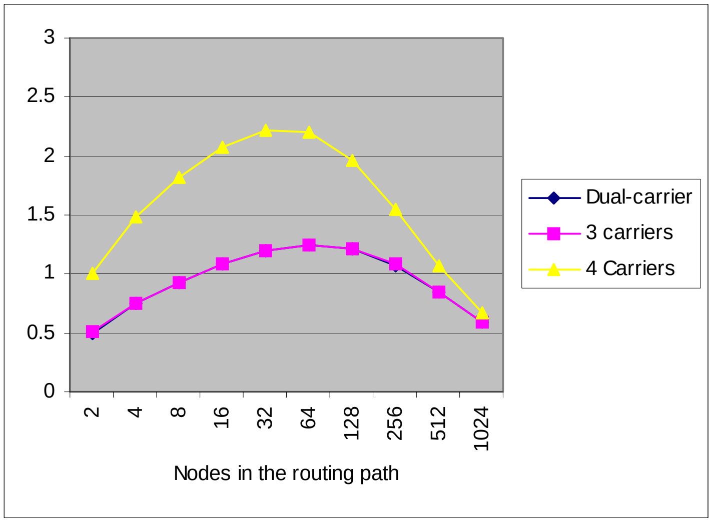

Figure 6: Latency ratio for single and multiple hop networks, with high signal to noise ratio 251, with α = 3.5 and packet lengths 200 times longer than the fragments.

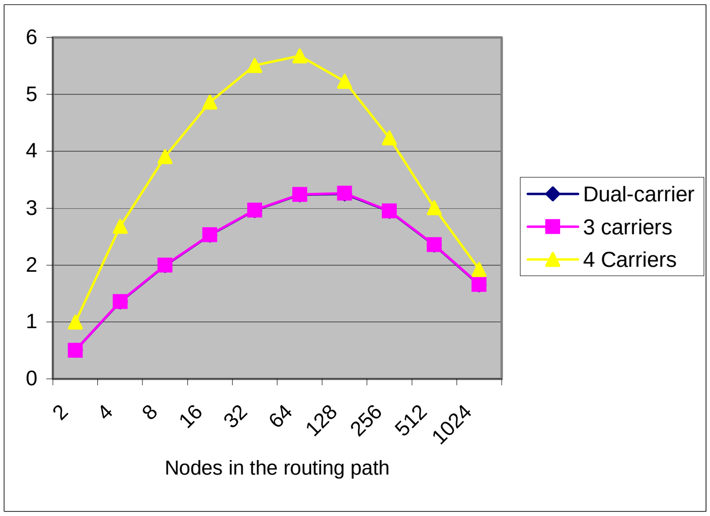

Figure 7: Ratio of the latency of a single hop to multi-hop ad hoc network with hop interferences, with low signal to noise ratio of 5, with α = 3.5 and packet lengths 200 times longer than the fragments