SPATIAL REUSE OF THE RADIO CHANNEL IN CDMA-ENABLED, AD-HOC WIRELESS SENSOR NETWORKS

Louise H. Crockett and Robert W. Stewart

Department of Electrical and Electronic Engineering, University of Strathclyde,
204 George Street, Glasgow, G1 1XW, Scotland, UK.
phone: + (44) 141 548 2605, fax: + (44) 141 552 2487, email: louise.crockett@eee.strath.ac.uk

ABSTRACT

To date, random access protocols like Carrier Sense Multiple Access (CSMA) have been the preferred means of sharing the radio channel in SpeckNets and other ad hoc wireless sensor networks. This paper considers Code Division Multiple Access (CDMA) as an alternative multiple access method, and evaluates the introduction of exclusion zones around each node as a low cost means of managing the Near Far problem. It is shown that, if appropriately sized zones are established, improved spatial reuse of the radio channel is possible (i.e. more concurrent transmissions can take place in proximity), potentially leading to energy savings in the MAC protocol.

1. INTRODUCTION

SpeckNets [11] are Wireless Sensor Networks (WSNs) with particularly stringent energy storage constraints, and are intended to be ad hoc, flexible, and mobile. They may comprise hundreds or even thousands of physically small nodes ("Specks"), and hence the problem of sharing the radio channel in an energy efficient manner is of particular concern. As is often stated in the literature, radio communication is the dominant consumer of energy within WSNs.

Without a central authority to monitor and co-ordinate access to the radio channel, nodes must contend for access. Whatever the channel access mechanism, a distance exists at which an interferer can cause irrecoverable damage to a desired transmission, as the interfering power received from this source is higher than the receiver can tolerate. As shown qualitatively in Figure 1, this distance may be far inside the transmission distance in CDMA systems (due to the near-orthogonal nature of the spreading codes used in CDMA), whereas the converse is true in non-spread systems.

Given that successful transmissions can take place with interferers in closer proximity in CDMA systems than in single channel, non-spread random access systems, CDMA is potentially attractive for WSNs (and indeed other ad hoc networks), because the radio channel may be reused more often in a spatial sense, i.e. more simultaneous transmissions can take place in a given physical space. From an energy perspective, this enhanced "spatial reuse" implies that contending transmitters can more readily access the radio channel, thus reducing the energy burden of the Media Access Control (MAC) protocol. Note that this definition of the term *spatial reuse* differs from another common interpretation: the distance between co-channel nodes (e.g. those operating on the same frequency in a cellular network).

This paper demonstrates that the Near Far problem experienced by simple, matched filter type CDMA receivers can be mitigated by placing a simple restriction on the transmission activity of Specks (i.e. creating an "exclusion zone" around each node, within which transmitters are prohibited), and that the required transmit power can be significantly reduced while providing the same area or volume of coverage. This low-complexity approach is appropriate to the SpeckNet context, where minimising power consumption is the overriding concern.

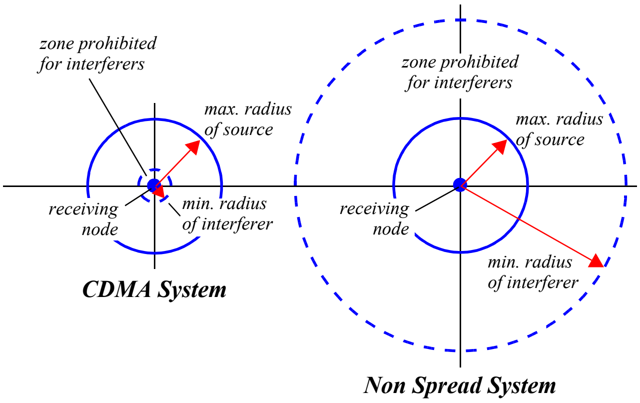

Figure 1 - The smaller interference radius in CDMA systems

The Multiple Access Interference (MAI) model developed in this paper is used to compare the spatial reuse possible in a candidate CDMA-enabled network with an equivalent random access, non-spread system, and it is shown that CDMA can offer a significant advantage. This comparison is based on the assumption of equal bandwidth and transmit power. Note that the relative powers of transceiver hardware are not considered in this work, which does not seek to evaluate the overall power consumed by a network. The realisation of a true *Speck*Net is likely to depend on shrinking process geometries and their associated power savings, while the MAI problem addressed here will remain the same. Associated topics which may be interesting for future work are the impacts of implementation losses arising from fixed point processing, and of imperfect synchronisation.

The rest of the paper is organised as follows: related work is reviewed in Section 2; Section 3 introduces the topology of the studied network; in Section 4, an analytical model for MAI experienced at an arbitrarily chosen node is developed, and the effect of introducing an exclusion zone around each node is evaluated; and Section 5 builds on this analysis to gauge the improvement in spatial reuse possible in a CDMA-enabled network. Finally, the paper is concluded in Section 6.

2. CONTEXT OF THE WORK

Much of the prior work on Near Far mitigation in ad hoc CDMA networks has assumed additional complexity - either in the MAC layer to perform local scheduling, in the receiver hardware, or both - and is aimed at more richly resourced networks than SpeckNets, where optimising throughput and latency are key priorities [1], [6], [8]. For example, although the authors of [1] consider the same problem using a similar model, they evaluate adaptive Successive Interference Cancellation (SIC) as an enabling receiver architecture, the computational complexity of which would be prohibitive for this application.

Spatial reuse in generic ad hoc networks has previously been studied from a link level perspective in [5] and [7]. However, the assumptions made in [5] include that noise can be neglected, and that nodes are distributed in a regular 1 or 2 dimensional pattern. Spatial reuse is assessed in terms of the distance between co-channel transmitter-transmitter pairs - a different definition than applies in the current analysis - with the optimum distance being that which maximises network capacity. Reference [7] also focuses on network capacity, and while it considers random node distributions, several assumptions differ from the work presented in this paper. In particular, the most basic of the scenarios covered involves scheduling based on Received Signal Strength (RSS), which is not directly applicable to the CDMA network considered here.

This paper is based on physical layer analysis, and contributes a comprehensive model of the MAI arising in an ad hoc CDMA network, wherein nodes are uniformly randomly distributed in 2 or 3 dimensional space, and the impact of both noise, and the specific interference properties of Gold codes, are included. By applying the model, it is shown that exclusion zones can be established around each receiving node and optimised to minimise transmit power. To the best of the authors' knowledge, this is the first analysis which focuses on minimising transmit power rather than maximising network capacity. Spatial reuse is assessed in terms of the area or volume around a receiving node within which transmitters must be silenced in order to fulfill bit error rate requirements.

Furthermore, for an example scenario, a quantitative comparison is made between the spatial reuse possible in a CDMA network, and a non-spread system in which nodes contend for access to a single frequency channel. The considerable advantage demonstrated in the CDMA case motivates future investigation of practical deployment considerations such as code allocation, and the co-ordination of transmission activity on a spatially aware but low energy basis.

3. NETWORK TOPOLOGY

Before proceeding, it is useful to define the topology of the network and associated terms, and to state relevant assumptions. As nodes are uniformly randomly distributed in two or three dimensions, the analysis is concerned with circular or spherical regions of space, and hence the terms "radius" and "distance" may be used interchangeably. Isotropic antennas are assumed.

Noting Figures 1 and 2, the following terms are used to describe the main features of the considered topology:

- **Maximum Transmission Distance / Radius (d_{max})** - the maximum distance over which a successful transmission can take place in a particular set of noise and interference conditions. In Figure 1, this is the maximum distance of a source from the origin, where the receiver is assumed to reside.
- **Exclusion / Prohibited Zone** - the area or volume adjacent to the receiver, within which interferers are prohibited. This is bounded by the distance (radius) *a*.

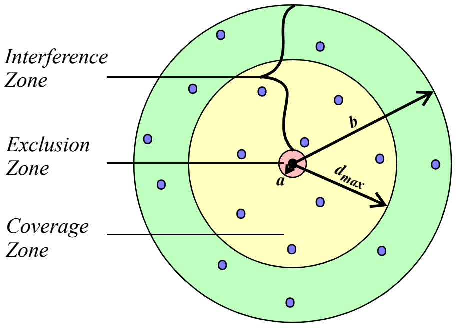

Figure 2 - An example 2D topology, illustrating the defined terms

- **Coverage Zone / Area** - in CDMA systems, the area or volume enclosed by the inner radius *a* and the outer radius d_{max}, e.g. a ring in the 2D case. This represents the region from which the receiver can successfully receive a transmission, in average interference conditions.
- **Interference Zone / Area** - the area or volume within which interferers are considered for interference analysis. This is the region bounded by inner radius *a* and outer radius *b*. The radius *b* is typically greater than d_{max}, and may be chosen such that an interferer at this distance contributes a known level of interference.

As an example, Figure 2 shows a network in which a random Speck has been chosen as the receiver. Transmissions from surrounding Specks can be received at distances up to d_{max}, in average interference conditions. Naturally, transmissions from further afield can contribute interference, even if they are too weak to be received correctly.

Correspondingly, interferers are considered up to a distance *b* from the receiver. Where an exclusion zone is created of radius *a*, the coverage zone is considered to be the ring bounded by *a* and d_{max}, while the interference zone is the ring bounded by *a* and *b*. It is assumed that all Specks in the network have fixed transmit power. However, the number of Specks transmitting in the region of interest, and the positions (and hence path losses) of these sources are variable. The analysis which follows is concerned only with the average (or "expected") conditions.

4. ANALYTICAL MODEL

It is well known that E_b/N_0 is a normalised version of signal to noise ratio applicable to digital systems, where E_b denotes the received energy per bit, and N_0 is the noise spectral density [10]. When analysing a CDMA network, an interference term I_0 is also included to represent the interference of the system. These quantities relate to the signal power (S), noise power (N), interference power (I), bit rate (R), spread spectrum bandwidth (W_{SS}) and processing gain (G_p) as follows,

$$\frac{E_b}{N_0+I_0} = \frac{S/R}{(N+I)/W_{SS}} = \frac{G_p S}{(N+I)}. \qquad (1)$$

The minimum level of $E_b/(N_0+I_0)$ is defined by the desired Bit Error Rate (BER) according to a standard curve, where $p(e)$ is the probability of bit error,

$$p(e) = \frac{1}{2}\left[1-erf\left(\sqrt{\frac{E_b}{N_0+I_0}}\right)\right]$$

and therefore, for any target BER, the user population is limited according to the amount of interference permitted.

Rearranging (1) and substituting for I gives an equation for signal power in terms of the expected noise and interference conditions,

$$S = \frac{\varepsilon}{G_p}[N + E(M)E(I_M)] \tag{2}$$

where $E(M)$ is the expected interfering node population, ε is used as shorthand for $E_b/(N_0 + I_0)$, and $E(I_M)$ is the expected interference power arising from an individual source,

$$E(I_M) = KP_{tx}E(\alpha)\,. \tag{3}$$

In (3), P_{tx} is the transmit power, and $E(\alpha)$ is the expected path loss of interferers, found using a probability density function for path loss [2], and K is chosen as 0.66 to reflect the cross-correlation properties of Gold codes (assumed throughout this paper) [3], [4]. Note that this differs from the value $K = 1$ implied in [1] and [6].

4.1 Maximum Transmit Distance and Coverage

By rearranging (2), and making the substitution

$$S = P_{tx}\left(\frac{\lambda}{4\pi d_{\max}}\right)^i$$

to reflect a simple path loss model with carrier frequency λ and path loss exponent i, the following expression is obtained for maximum transmission distance,

$$d_{max} = \frac{\lambda}{4\pi\sqrt[i]{\frac{\varepsilon}{G_p P_{tx}}(N + E(M)E(I_M))}} \tag{4}$$

As stated previously, this is the greatest distance, on average, at which a transmission can be successfully received in the defined noise and interference environment. The corresponding coverage area or volume can be found using (5) or (6) for 2D or 3D deployments, respectively.

$$A_R = \pi(d_{max}^2 - a^2) \tag{5}$$

$$V_S = \frac{4}{3}\pi(d_{max}^3 - a^3) \tag{6}$$

4.2 Maximising Coverage Area or Volume

By expanding (4) and making the appropriate substitutions for $E(\alpha)$, two different expressions are obtained for d_{max} in each of the two- and three-dimensional cases. In 2D, (7) applies when the path loss index $i = 2$, and (8) applies for all other path loss indices. Similarly in 3D, (9) is used when $i = 3$, and (10) in all other cases. The symbol γ is used to represent the intensity of transmitting Specks in nodes per m^2 or m^3.

$$d_{max} = \frac{\lambda}{4\pi\sqrt{\frac{\varepsilon N}{G_p P_{tx}} + \frac{\varepsilon K\gamma\lambda^2(\ln(b) - \ln(a))}{8\pi G_p}}} \tag{7}$$

$$d_{max} = \frac{\lambda}{4\pi\sqrt[i]{\frac{\varepsilon N}{G_p P_{tx}} + \frac{2\pi\varepsilon K\gamma\left(\frac{\lambda}{4\pi}\right)^i\left(\frac{b^{2-i} - a^{2-i}}{2-i}\right)}{G_p}}} \tag{8}$$

$$d_{max} = \frac{\lambda}{4\pi\sqrt[3]{\frac{\varepsilon N}{G_p P_{tx}} + \frac{\varepsilon K\gamma\lambda^3(\ln(b) - \ln(a))}{16\pi G_p}}} \tag{9}$$

$$d_{max} = \frac{\lambda}{4\pi\sqrt[i]{\frac{\varepsilon N}{G_p P_{tx}} + \frac{4\pi\varepsilon K\gamma\left(\frac{\lambda}{4\pi}\right)^i\left(\frac{b^{3-i} - a^{3-i}}{3-i}\right)}{G_p}}} \tag{10}$$

The covered area or volume can therefore be expressed in terms of the exclusion radius, a, by substituting these equations into (5) and (6). Coverage can be maximised by carefully choosing a, i.e. excluding Specks from transmitting within a certain optimum radius of the receiver. The resulting expressions for the 2D cases are given by the next two equations, which correspond to (7) and (8). (Note the 3D versions are omitted from here on due to space constraints, but these equations can be developed using the same method.)

$$A_2 = \frac{\lambda^2}{\left(\frac{16\pi\varepsilon N}{G_p P_{tx}} + \frac{2\varepsilon K\gamma\lambda^2(\ln(b) - \ln(a))}{G_p}\right)} - \pi a^2$$

$$A_i = \frac{\lambda^2}{16\pi\left(\frac{\varepsilon N}{G_p P_{tx}} + \frac{2\pi\varepsilon K\gamma\left(\frac{\lambda}{4\pi}\right)^i\left(\frac{b^{2-i} - a^{2-i}}{2-i}\right)}{G_p}\right)^{\frac{2}{i}}} - \pi a^2$$

Figure 3 provides an example, plotting maximum transmission distance (d_{max}) and coverage area ($A_{i=2.5}$) against exclusion radius (a) for the parameters given in the appendix (Section 7). In this case, choosing a as the optimum value produces an 254% increase in coverage area compared to the case without an exclusion zone, where it is assumed that $a = \lambda$. (Note the restriction $a \geq \lambda$, due to the invalidity of the simple path loss model within this range.)

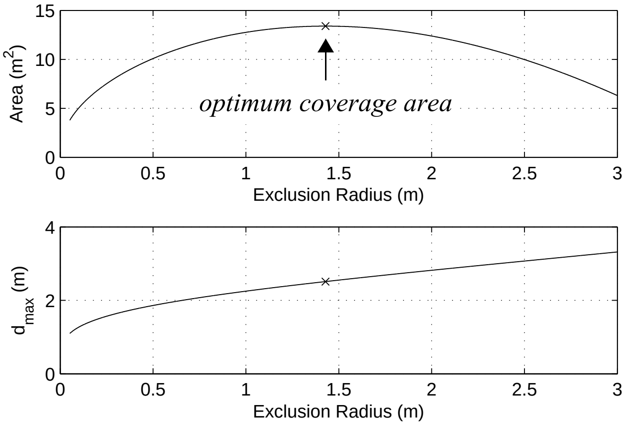

Figure 3 - Variation of maximum transmit distance (d_{max}) and coverage area, with exclusion zone radius (a).

4.3 Minimising Transmit Power

Coverage area or volume can be maximised for a fixed transmit power, and hence it follows that transmit power can be minimised for a fixed coverage region. The optimum power can also be calculated as a function of a, with the target coverage area or volume represented by A_0 or V_0, respectively. Again, this analysis results in a set of four equations, corresponding to the conditions stated in Section 4.2. The pair presented here (equations (11) and (12)) relate to the two dimensional case, firstly for path loss exponent $i = 2$, and secondly for all other path loss indices.

$$P_{tx_{opt}} = \frac{8\pi N}{\dfrac{G_p\lambda^2}{2\varepsilon(A_0+\pi a^2)} - K\gamma\lambda^2(\ln(b)-\ln(a))} \qquad (11)$$

$$P_{tx_{opt}} = \frac{N}{\dfrac{G_p}{\varepsilon}\left(\dfrac{\lambda^i}{16\pi((A_0+\pi a^2))^{(i/2)}}\right)} - \frac{N}{-2\gamma\pi K\left(\dfrac{\lambda}{4\pi}\right)^i\left(\dfrac{b^{(2-i)}-a^{(2-i)}}{2-i}\right)} \qquad (12)$$

Adopting the same example parameters as previously, a graph of transmit power against exclusion radius can be drawn, as shown in Figure 4. The value of *a* which minimises transmit power is marked. Note that a significant reduction is achieved even for *approximately* the correct value (which is a more realistic assumption in a real deployment).

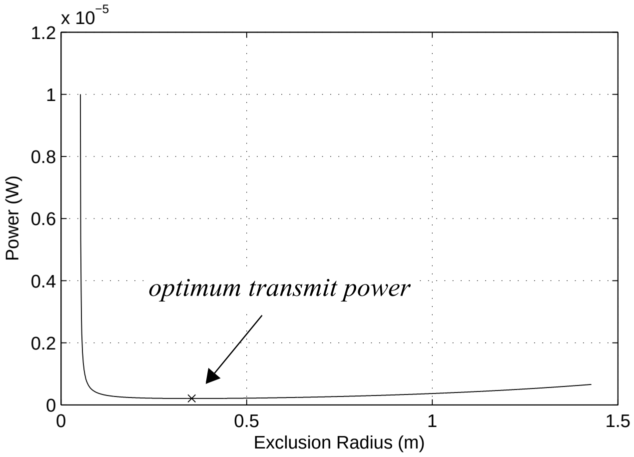

Figure 4 - Variation of transmit power with exclusion radius (*a*)

4.4 Summary of Results

Figure 5 compares the powers and coverage areas resulting from the three scenarios presented, namely:

1. The original transmit power (P_{tx}), and without an exclusion zone ($a = \lambda$ is used for analysis).
2. The original transmit power (P_{tx}), and with the exclusion radius set to maximise the covered area.
3. The original area (A_0), with the exclusion zone radius set to minimise transmit power ($P_{tx_{opt}}$).

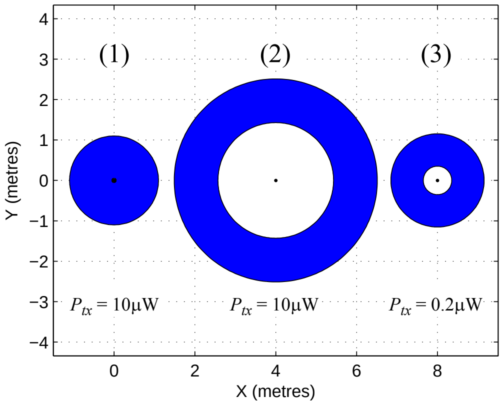

Figure 5 - Comparison of coverage areas and transmit powers

The main implication of these results is that Quality of Service (QoS) requirements can be met using a significantly reduced transmit power, simply by restricting the positions of transmitting Specks. In a network like a SpeckNet, which already incorporates duty-cycling, and redundancy to cater for node failure, this could be achieved by coordinating the "sleeping" of Specks in a spatially intelligent manner.

5. SPATIAL REUSE

In the introduction, it was qualitatively shown that CDMA systems have smaller interference radii than non-spread systems. In this section, the difference is quantified for an example scenario, and linked to spatial reuse - the distance at which concurrent transmissions can take place simultaneously while achieving the required BER, in average conditions. The exclusion radius defines the area or volume effectively "consumed" by a transmission.

Fair comparison requires a non-spread system with equal transmit power, and which is equivalent to the CDMA system in the sense that their signaling rates (and hence bandwidths) are the same. This non-spread model requires three changes from the CDMA version.

Firstly, as a result of the higher bit rate, transmission intensity is lower than the CDMA system by the factor G_p, i.e.

$$\gamma_{ns} = \frac{\gamma_s}{G_p}$$

(where the subscripts *s* and *ns* denote the spread and non-spread systems, respectively). The limit of the interference zone, *b*, is also defined differently. In the spread system, it is assumed that interferers are considered within the radius at which despread interference is 10dB below the noise floor,

$$b_s = \frac{\lambda}{4\pi\sqrt[i]{\dfrac{N}{10KP_{tx}}}},$$

whereas in the non-spread system, the Gold code constant, *K*, is omitted. Likewise, (3) is amended to omit *K*. The result of these changes is an equation equivalent to (4) for the non-spread case,

$$d_{max} = \frac{\lambda}{4\pi\sqrt[i]{\dfrac{\varepsilon}{P_{tx}}(N+E_{ns}(M)E_{ns}(I_M))}}$$

Expanded equations for the four different topology and path loss scenarios can be developed from this.

The spatial reuse comparison adopts the following procedure:

- Assume that the maximum transmission distances of the spread and non-spread systems are equal, i.e.

$$d_{max_s} = d_{max_{ns}}.$$

- Rearrange the resulting equation for a_s, the exclusion radius of the spread system.
- Evaluate a_s as a_{ns} is varied (with other parameters fixed).

For example, the resulting expression for a 2D deployment with path loss $i > 2$ is given by (13).

It is assumed that transmit power is fixed, and that a_s is optimised for coverage area. Additionally, note that while realisable values of G_p for Gold codes are limited [4], [9], intermediate values are plotted in Figure 7 for visualisation purposes, with valid Gold code

$$a_s = \sqrt[(2-i)]{-\frac{G_p}{K\gamma_s}\left(\frac{(2-i)N\left(1-\frac{1}{G_p}\right)}{2\pi P_{tx}\left(\frac{\lambda}{4\pi}\right)^i}+\gamma_{ns}(b_{ns}^{(2-i)}-a_{ns}^{(2-i)})\right)+b_s^{(2-i)}} \tag{13}$$

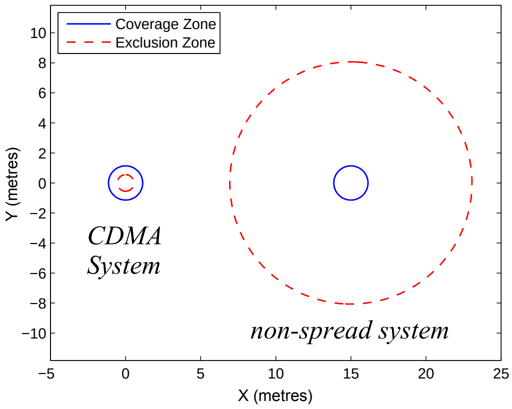

Figure 6 - Quantitative exclusion zone comparison for $G_p = 63$

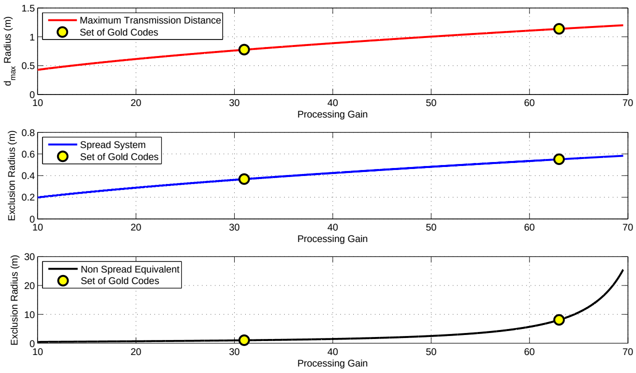

Figure 7 - Comparison of spatial reuse in terms of distance

lengths highlighted by markers. Figure 6 illustrates spatial reuse for $G_p = 63$, thus quantitatively supporting the assertion of Figure 1.

6. CONCLUSIONS

This paper has addressed the issue of low complexity mitigation of the Near Far problem in ad hoc WSNs. A physical layer model of MAI has been developed and applied to minimise node transmit power. It has also been shown that, if a suitable exclusion zone can be established around each receiving node, the radio channel can be reused more often in a spatial sense, i.e. transmissions can take place successfully in closer proximity than in a non-spread system.

This result is significant from an energy perspective, as it implies that more transmissions can proceed at the first attempt (thus reducing the overhead of sensing the channel and backing off), with fewer packets lost due to the hidden terminal problem.

7. APPENDIX

Table 1 details the parameters adopted for the illustrative examples presented in this paper (unless stated).

Note that the intensity of transmissions, γ, is given by $\gamma = pn$, where n is the density of nodes in the network, and p is the probability of an individual node transmitting.

Table 1: Parameters for Numerical Examples

Parameter	Unit	Value
Path loss index (i)	-	2.5
Carrier frequency	GHz	5.8
Transmit power (P_{tx})	μW	10
Transmission intensity (γ)	nodes/m^2	5
Processing gain (G_p)	-	1023
Bit rate (R)	bps	5000
Receiver bandwith (ideal) (B)	Hz	G_p x R
Noise spectral density (N_0)	dBm/Hz	-143.8
Target Bit Error Rate (ε)	-	1e^{-3}
$E_b / (N_0 + I_0)$ required for target BER	-	6.79dB

8. ACKNOWLEDGEMENT

The authors would like to thank the Consortium in Speckled Computing for supporting this work.

9. REFERENCES

[1] J. G. Andrews, S. Weber, and M. Haenggi, “Ad Hoc Networks: To Spread or Not to Spread?”, *IEEE Communications Magazine*, December 2007, pp. 84 - 91.

[2] L. H. Crockett, "On Code Division Multiple Access Applied to SpeckNets", *Ph.D thesis, University of Strathclyde, 2008.*

[3] E. H. Dinan, B. Jabbari, “Spreading Codes for Direct Sequence CDMA and Wideband CDMA Cellular Networks,” *IEEE Communications Magazine*, Vol. 36, Issue 9, September 1998, pp. 48 - 54.

[4] R. Gold, “Maximal Recursive Sequences with 3-Valued Recursive Cross-Correlation Functions,” *IEEE Transactions on Information Theory*, Vol. 14, Issue 1, January 1968, pp. 154 - 156.

[5] X. Guo, S. Roy and W. S. Conner, “Spatial Reuse in Wireless Ad Hoc Networks”, *Proceedings of the 58th IEEE Conference on Vehicular Technology*, October 2003, Vol. 3, pp. 1437-1442.

[6] A. Hasan and J. G. Andrews, “The Critical Radius in CDMA Ad Hoc Networks,” *IEEE Global Telecommunications Conference (Globecom),* 2004, Vol. 6, pp. 3568 - 3572.

[7] S. Max, E. Weiss and G. R. Hiertz, “Benefits and Limitations of Spatial Reuse in Wireless Mesh Networks”, *Proceedings of the 10th International Workshop on Modelling, Analysis and Simulation of Wireless and Mobile Systems*, Greece, 2007, pp. 244-251.

[8] A. Muqattash and M. Krunz, “CDMA-Based MAC Protocol for Ad Hoc Networks,” *Proceedings of the 4th International Symposium on Ad Hoc Networking and Computing*, 2003, pp. 153 - 164.

[9] D. V. Sarwate and M. B. Pursley, “Crosscorrelation Properties of Pseudorandom and Related Sequences,” *Proceedings of the IEEE*, Vol. 68, No. 5, May 1980, pp. 593 - 691.

[10] B. Sklar, *Digital Communications: Fundamentals and Applications*, 2nd Ed.,Prentice Hall, 2001.

[11] Speckled Computing - http://www.specknet.org/