Creating and Exploiting Intangible Networks: How Radiata was able to improve its odds of success in the risky process of innovating[1]

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Summary

This case study demonstrates how one form of intangible network, a wireless *Local Area Network* (LAN) based around a single semiconductor chip developed by an Australian company Radiata, was made possible by the strategic development and subsequent use of another type of 'intangible' network. This second type of intangible network consists of networks of highly-skilled people who know and trust each other. These networks can be critical to achieving more favourable odds in the inherently risky process of innovating. Radiata Communications Pty Ltd developed a single microprocessor-based wireless Local Area Network (LAN) device that complied with a new international standard for wireless LAN systems. Following interim investments by Cisco Systems and another company called Broadcom, Radiata was eventually acquired by Cisco Systems for AUS$567m in November 2000 (with the deal finalised in January 2001). Radiata is now widely cited as an example of successful research commercialisation in Australia.

The Radiata case study shows how the pre-existing innovative capacity created by a domestic network associated with Australian radio-astronomy and electronic engineering was utilised by Australian entrepreneurs benefiting from exposure to US networks and business practices. The ability to develop semiconductor chips that integrated modem and radio functions via a minimum number of costly and time-consuming design iterations was a critical intangible asset. This ability was based upon a thorough understanding of how best to use available state-of-the-art Computer Aided Design (CAD) tools for designing CMOS integrated circuits. These design tools allow the number of iterations in design and development to be minimised. This dramatically reduces the time and cost required to complete the 'D' component of R&D (ie. experimental development). The combination of these three key 'intangible' assets, combined with strategic efforts to identify business opportunities within the regulatory framework provided by a new international standard for wireless LANs, were critical to success. The odds of success were never that high, but the existence of these networks and the ways in which they were exploited generated far better odds of success than would otherwise have been possible.

The main lesson learnt for science and innovation in Australia is that attention needs to be focussed upon the intangible 'asset values' created by networks of highly skilled scientists, engineers and entrepreneurs. These asset values are based upon an increased probability of success in innovating. This is turn is related to an increased probability of achieving a high proportion of design targets on the first major design iteration, thereby maximising the speed and minimising the cost of the overall design and development process. The availability of technologies that allow the time and cost of completing experimental development ('D' in R&D) to be minimised provide the scope for skill and experience to substitute for higher levels of investment in the innovation process. This competitive opportunity based upon 'low D R&D' is of particular importance to a small economy like Australia that does not have the advantage of economies of scale in finance for innovation. $1m goes a long way in research but is quickly spent on development. Being unusually smart about how we do R&D therefore partly offsets the disadvantages of being a small economy.

Fostering the capacity to use these networks and skills in such a way that the location-specific disadvantages of attempting to innovate in Australia are minimised is therefore important. Radiata presented itself as a US company carrying out R&D in Australia. This argument was key to 'selling' the investment proposition on the basis of the reduced investment risks that this scenario generated. Globalisation provides an opportunity for Australian innovators to offset any risk-inflating disadvantages that stem from innovating in Australia, whilst also allowing any locational advantages to be exploited - such as cost-effective R&D. However, this juggling of these locational advantages and disadvantages can only be achieved if the game is played explicitly on this basis. International experience and contacts together with state-of-the-art research infrastructure are critical to being able to play such a role in the global innovation system. By implication, an insular Australia-focussed approach would increase the investment risks faced and consequently decrease innovative capacity.

Introduction

"The boundary between invention and innovation is the place where individual human ingenuity connects with long-term macroeconomic growth". (Branscomb and Auerswald, 2001, page 1)

Innovation is inherently risky and involves a strong element of 'learning-by-doing'. The greater the experience in innovating the lower the risk of failure faced when attempting to innovate. The value of this experience is recognised by venture capitalists, who prefer to invest in ventures in which the key proponents have prior experience of the incredible complexity and range of risks faced in the innovation process. This knowledge of how to navigate the 'white-water' risks faced when innovating is highly tacit and is therefore not easily taught outside of actual experience.

This learning-by-doing is not just personal, there is also a collective dimension. The groups of people who have innovated, or tried to innovate, gain valuable collective experience. This amounts to an intangible asset for a region or national economy. This is why US venture capitalists often invest strategically in industries rather than exclusively on the basis of case-by-case propositions. Investing in industries allows the intangible asset of collective experience and its associated flows of experienced people between different countries to be exploited. Economists call this type of intangible asset a 'positive externality'.

The movement from invention to innovation, that is to say the *commercialisation* of an invention, involves taking abnormally high investment risks in order to generate the (usually remote) possibility of making abnormally high returns. When this process is particularly successful the result is, in statistical terms, an 'outlier' – a rare event that deviates from the norm. Comparatively little attention is paid to these outliers in economics and econometrics because these events are viewed as transient phenomenon that reflect a temporary disturbance to normal competitive circumstances. Business schools also devote comparatively little attention to the leap from invention to innovation because these are, by definition, 'pre-competitive' activities. We therefore face not only a major gap in progressing from invention to innovation in terms of the capacity to manage the abnormal risks involved, we also face sparsely populated regions in the academic literature that analyse these processes (Hartmann and Myers, 2001).

Nonetheless, these 'outliers' often have a significant effect upon national and regional prosperity – and can sometimes create whole new industries or market segments. From a policy perspective, although one cannot develop policies and commercialisation strategies based upon what are, in statistical terms, 'lightening strikes', one can seek to create more favourable conditions and incentives to encourage appropriately skilled people to take these abnormal risks. If these risks are not taken then the probability of creating these beneficial outliers in the distribution of returns against investments all but disappears. The objective is to create more favourable odds of generating abnormally high rates of company growth, but with no strong expectation that this can be forecasted or predicted on a case-by-case basis.

It is in this latter respect that encouraging research commercialisation by spin-offs, start-ups and licensing deals (all of which have merits) can clash with the 'risk-averse' approach to setting tightly specified performance targets in the public sector (ie. clearly defined outputs and outcomes). The inherently risky nature of commercialisation, particularly as one seeks to move along the learning curve associated with improving the odds of success by trial and error, means that failures are to some extent inevitable – *but that these failures are valuable*. Unless we have a policy framework that explicitly recognises the value of learning-by-doing in investment risk management we may overlook the cumulative value of our history of successes *and* failures. Whilst we cannot base lessons for policy-making upon simply exploiting luck, we can examine the extent to which both the public and private sectors can develop strategies and tactics to buy better odds of success. Luck will still play a part, but we should aim to have more control over the odds that we face.

Attempting to innovate in Australia, as in any other country that possesses less collective experience of innovation than a country like the United States necessarily involves navigating unusually high risks. This is because the already severe risks faced in trying to innovate in a country like the United States are further increased by *not* doing this in the United States. There is less collective experience, less personal experience to draw upon, and there may even be some structural disadvantages, such as unhelpful cultural attitudes to risk-taking.

This case study focuses upon some long-term strategic investments in building networks of capability to innovate and on some, perhaps more unintended consequences of these decisions. These networks are embodied in people. They have generated better odds of success in the innovation process, and these improved odds of success have been exploited for significant commercial gain. The case-study focuses upon a collective effort to exploit radio-physics based technological advances in radio-astronomy in a highly strategic manner. These efforts paid off by creating a number of start-up companies, the most successful of which (to date) is Radiata. Radiata was purchased by Cisco Systems for AU$567m in 2000.

Some key lessons emerge from the Radiata story that are relevant to science and innovation in Australia. These are:

- the importance of 'blue sky' basic research in establishing demanding technological requirements for research instruments that, in turn, have wide-spread practical applications;
- the nature and extent of Australia's inter-personal network-based 'intangible assets' used in innovation and the strategic management of people's careers in order that they obtain multi-sector experience;
- the significance of these intangible assets for mapping our innovation capabilities in terms of their impact upon investment risk management;
- how the 'science-push' ethos meshes with a 'demand-pull' ethos in the face of these risks;
- the sustained long-term planning and activities necessary to create these innovation networks (today's short-term tenures and more highly contested funding arrangements may limit this capacity);
- the role of international standard-setting procedures in creating market opportunities;
- the importance of fostering 'low D R&D' by combining high skill and substantial experience with state-of-the-art computer-based engineering design tools;
- how government programs can help entrepreneurs to manage investment risks through exposure to global experience and business practices;
- the long timeframes sometimes required for innovation to take place when we consider the capacity-building efforts that precede specific innovative episodes.

This case study has three components. Firstly, in Part One there is the story of the specific decisions and events that led to Radiata being formed and developing as a potentially successful business, culminating in its acquisition by Cisco Systems in 2000. This part of the story is about how a pre-existing capacity to carry out research and innovation was used. There is also a story to be told about the ways in which this under-pinning research and innovation capacity *itself* was developed as the product of long-term strategies. Part Two therefore discusses briefly the broader, longer-term, capacity-building activities leveraged by those involved in Radiata. Part Three of the study discusses the more general implications of Radiata story and its 'pre-history' within the specific context of the science and innovation mapping exercise.

A number of people played a role in these developments, some currently in the limelight and some behind the scenes. In order to avoid under-playing the importance of some people by giving prominence to selectively named individuals this case study focuses upon the *ideas*, *teams* and *skills* that were developed and deployed rather than upon giving credit to particular individuals. These are after all largely team-based efforts, indeed the building of the capacity for team work plays a large part in the story. Invention and innovation is more often than not a *social process* involving 'communities of practice'. The intention in this paper is to highlight these group dynamics and to explore some of their policy implications. Consequently, a general list of the individuals involved and a brief description of their role(s) is provided in Annex B. Individuals are only named in the text when a published source or quote from a personal communication is cited.

Part One: The Radiata Story

"we really admire your spirit but you haven't got a hope in hell of it working"

Comment to Radiata made by a leading US industry expert on GSM chips, July 2000.

"Cisco Systems has announced the global launch of its wireless local areas network products, marking the first use of the technology it bought for $567 million through its acquisition of an Australian company, Radiata, in November 2000."

Australian Financial Review, 23rd April 2002.

Defining the problem

There are two dimensions to the innovation process that resulted in the development of effective wireless Local Area Network (LAN) technologies. Firstly, the growing awareness of the market potential for wireless LANs. Secondly, the specific ideas on how to solve the technical challenges. In this case, the notion that 'Fast Fourier Transform' (FFT) techniques could provide a solution.

With regard to the growing awareness of the market potential for wireless LANs, the underlying assumption in the late 1980s was that short distance wireless communication could be a major market area in the future as various users of electronic equipment sought to maximise the flexibility and inter-connectivity of different types of device. The technical challenge was that the signals used for wireless communication in the available frequency ranges bounce off the walls, floor, ceiling and furniture, creating a highly complex three-dimensional system of pathways between the transmitter and the receiver.[2] In moving between the transmission source and the receiver each packet of information travels a different distance, and consequently arrives at the receiver at a slightly different time. This has the same sort of effect as the 'ghosting' (duplicated weaker images) in television pictures caused by signals bounced from nearby buildings being integrated into the signal.

Consequently, in the late 1980s a number of research teams started to think about the market potential of wireless LANs, and therefore started to think about the various technological solutions that might be developed in order to turn this concept into a reality. This interest was not restricted to Australia, researchers in major US corporations were also starting to think through the commercial and technological logic of developing technologies in this area. As members of this international community, researchers in the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Radiophysics Division and at Macquarie University's Electronics Department started to become active in considering both the overall market potential and the specific technological solutions that could be developed.

During this era, the Cooperative Research Centre (CRC) Programme was launched with the stated aim that "*Australia must match the technology push provided by its strong research base with the demand pull of industry and other research users*".[3] Macquarie University and CSIRO, who were already working collaboratively in this area joined forces along with industry partners to

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[2] The extent to which this bouncing takes place depends upon the precise frequencies used. The spectral band from 54GHz to 65GHz is strongly absorbed in the atmosphere and is therefore not suited to long-distance communication. It is suitable for LAN distances however, even though the wave propagation properties are 'quasi-optical'. Skellern et al (1996).

[3] Media Release announcing the first 15 CRCs, Minister for Science, 14 March 1991.

submit a proposal to the new CRC Programme to establish a 'Centre for Local Environment Communications Technology'. The proposed CRC aimed to develop advanced engineering design methods, performance prediction techniques, implementation and test methods that would facilitate the development of cost-effective advanced wideband wireless networking systems. This engineering work had a clear market focus, as the 1990 proposal noted in what, with hindsight, is a prophetic observation: "*Wireless services are now in their infancy and demand for wideband wireless networks will evolve dramatically over the next decade driven largely by commercial pressures*". However, the proposed CRC was not funded and the collaborative R&D continued by using available funding and resources in CSIRO Radiophysics Division and Macquarie University's Electronics Department.

Turning to the proposition that 'Fast Fourier Transform' (FFT) techniques could provide a means of overcoming some of the many technical challenges faced, FFT is a mathematical technique that allows signals to be divided up, transmitted, and then re-combined in such a way that the complex reflections found inside buildings can be handled. Orthogonal Frequency Division Multiplexing (ODFM) is the term used to describe this application of FFT. Annex A contains a technical account of how FFT and ODFM works in the wireless LAN context. The CSIRO Radiophysics team put forward the idea of creating wireless broadband networks by using 'Fast Fourier Transform' techniques to divide up the spectrum in such a way that the complex reflections found inside buildings could be handled. At a time when CSIRO was re-structuring an increased focus on applicable research in telecommunications (signal processing, wireless communication and imaging work) in collaboration with the team of electronic engineers at Macquarie University appeared to be a sensible and pragmatic step.

Developing a Solution

CSIRO decided to fund some exploratory work on the use of FFT in wireless LANs, initially to a level in the region of $200,000 subsequently increasing to nearly $1m in a follow-up project. A relatively high carrier frequency of 60 GHz was initially selected. This was because CSIRO's existing expertise lay in the radio astronomy and microwave landing systems that operate in this high frequency range.

The initiative was known as the 'Program for Local Area Networks' (PLANs) and involved the team at Macquarie University with the collaboration centred around chip design, network and decoder design. Eventually, a joint research centre linking these two organisations was formed in 1993.

The mid-1990s were a difficult period for the joint research centre. IBM pulled out as a partner and the Europeans selected a different wireless LAN technology than the Australians were developing.[4] As the head of CSIRO's Division of Radiophysics at the time observed "*There was mounting opposition within the CSIRO division to even continue with the project*".[5] The response to this uncertainty was to proceed with a CSIRO-funded demonstrator project within Macquarie University in order to attempt to counter-act the growing scepticism over the attractiveness and the feasibility of this technological solution. The research was also supported by Australian Research Council (ARC) grant funding to Macquarie University. The ARC funding helped to support the underpinning R&D infrastructure used by the researchers

By 1995 an ODFM system had been demonstrated that was able to overcome the severe problems faced in an indoor multi-path environment. This demonstration technology was able to operate at 100Mbps (100M bits per second). The researchers in the joint research centre published their work (see for example Skellern et al, 1995). Based on the (fairly high) level of disclosure of information it appears to be the case that consideration of any commercial applications would rest

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[4] The European approach, Hiperlan, adopted a different frequency range and initially did not use ODFM.
[5] Cooper (2001), page 42.

upon more tacit and proprietary capability to actually engineer the solution within the demanding cost, power and heat generation parameters. This was intentionally 'commercially applicable' research but not commercially confidential research.

This work led to a US patent being granted in 1995 (assigned to CSIRO by the inventors) for a wireless Local Area Network (LAN). [6] Given the importance of tacit knowledge and speed to market in the electronics sector, obtaining a patent was not, reportedly, viewed by the researchers as a major priority at the time (Cooper 2001). Only one of the inventors named in the patent subsequently became involved in forming Radiata. The CSIRO patent (which is available on-line on the US Patent Office web site) describes in some detail the rationale and circuit design details required to transmit data in a wireless LAN. It makes 72 specific technical claims. CSIRO decided to license this technology on a non-exclusive basis. The CSIRO patent covers 802.11a, 802.11g and 802.11j wireless LAN standards – which makes it potentially valuable in this growing market.

Forming Radiata and managing investor perceptions

During this initial period in the development of wireless LAN technology one of Radiata's founders was working in the United States. In 1998 there were negotiations between CSIRO and Macquarie University in order to create an attractive half-time position at the University in order to lure this well-regarded microprocessor designer back to Australia. At that time there was a 'vague notion' to form a company at some point to exploit opportunities in the wireless LAN field, but this was not a major motivation for attracting him back to Australia. The funds to bring him back as a professor were provided by CSIRO via the joint research centre and those involved in these discussions recall that the university usefully adopted a flexible attitude towards this arrangement that both helped it to be attractive to him and made it work in practice once he had arrived in Australia.

Once established at the University he started to put in place some of the people and equipment required to make a 'commercial excursion' into chip design. This involved a move into commercial Computer Aided Design (CAD) tools – with CAD tools with a commercial street value of US$6m being supplied to the Macquarie team by a US CAD company at zero cost. A deliberate effort was made to target circuits of potential interest in developing wireless LANs. A team was trained in how to use with CAD equipment and external contractors were used when necessary – some of whom were then hired by the research team (Weste, 2002). One product of this work was the development of a complete modem chip, the DMT-50. This incorporated FFT technology from a previous FFT chip design developed at the joint research centre in 1996. It appears to be the case that work on the DMT-50 chip started before Radiata was formed and was completed in 1998 as part of Radiata's design work.

Radiata Inc. (a contraction of the term "radio data") was formed in 1997 primarily in response to the market potential created when the 5GHz-based spectrum for wireless LANs became available as part of the *US National Information Infrastructure* (NII) policy initiative. The NII was part of Vice-President Al Gore's famous 'invention' of the Internet because the NII made the 5GHz part of the spectrum available for use by schools to connect to the Internet. The 5GHz range has the advantage that it is relatively un-congested. Bluetooth, which operates at 2.4GHz, shares spectrum with cordless telephones, micro-wave ovens and devices like baby monitors.

[6] US Patent Number 5,487,069 entitled 'Wireless LAN' was issued on January 23rd 1996 and filed on November 23rd 1993 with a foreign application priority date of November 27th 1992. This patent was assigned to the CSIRO by the five named inventors (John O'Sullivan, Graham Daniels, Terence Percival, Diethelm Ostry and John Deane (all Australian residents). The CSIRO patent cited seven prior US patents and also has a cross-reference to Australian patent number 610,934 – which related to a FFT processing circuit design.

The parent company was incorporated in the US State of Delaware.[7] It established an Australia-based R&D operation Radiata Communications Pty Ltd and a California-based sales and marketing operation known as Radiata Communications Inc. Radiata's intellectual property (IP) was 'generally related' to IP developed at the joint CSIRO-Macquarie University research centre. However, the company's informal IP (know-how) also contained substantial accumulated expertise in designing different types of integrated circuits. The terms of the arrangements for handling IP in the joint research centre were that developments would be shared jointly by the two parties. However, some specific elements of the technology licensed to Radiata involved a deal solely with CSIRO. This was because Macquarie University had no specific rights to the wireless LAN patent held by CSIRO – the patent that related to one solution to meeting the IEEE 802.11a specification. It is also understood that other IP associated with the DMT-50 chip was sold by Macquarie University to Radiata.[8]

It is plausible that the licence arrangement with CSIRO was beneficial compared with a more direct involvement by CSIRO because the ability to conclude subsequent deals quickly would have been reduced if CSIRO's stringent legal processes were on the critical path. The licence arrangement avoided this problem. An inability to do deals quickly would have created a major impediment in dealing with the US ICT companies with whom deals were eventually struck and with the venture capital companies with whom negotiations did take place.

Radiata was deliberately modelled on a Silicon Valley company. This involved an egalitarian management philosophy, informal working conditions and the widespread use of share options. That said, it turned out that many of the employees were happy to accept share options, but had little understanding of what they were and of their significance.

Shortly after Radiata had been formed the new IEEE 802.11a standard for 5GHz wireless LAN networks was defined. It seemed to be clear at the time that IEEE 802.11a represented a potentially lucrative market - although it was unclear how this standard could be addressed in detailed technological terms (particularly in relation to a small, low power consumption solution). The technical challenges were immense but the market potential appeared to exist.

Market potential is one thing, being able to enter this market without going bust in the process is another. The existence of a new international standard for wireless LAN communication at 5GHz had a significant impact on the investment risks faced in the commercialisation process. IEEE 802.11a defined the key performance parameters for the engineering decision-making process. This tight focus reduced the range of potential technological options that might have to be considered. It also restricted the scope and complexity of the engineering trade-offs faced. Although still representing major challenges for the engineering process, 802.11a's performance envelope would effectively turn uncertainty into *risk*. The translation of uncertainty into risk is a critical stage in the commercialisation process. The challenge for the next phase of the innovation process becomes that of generating sufficiently favourable technical and business risks that subsequent larger-scale investment funding can be obtained.

Opinion differs on the ways in which the existence of CSIRO's wireless LAN patent influenced the subsequently agreed 802.11a standard. Before discussing this issue it is worth noting that the way in which competing companies manage to agree standards for technology is, not surprisingly, fraught with difficulties. Representatives of competing companies meet to argue and try to agree shared technical standards. These standards focus competition in defined areas and give some coherence to markets by allowing different companies' products to work together and to be substitutes for each other. Without such standards the resulting technical confusion limits the extent to which a market can expand and therefore allow profits to be reaped from economies of scale in production. Although there are committee structures associated with different international

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[7] Incorporating in Delaware has widely recognised tax and regulatory advantages.
[8] According to material placed on the Macquarie University Electronics Department web site.

groups (such as the IEEE)[9] involvement is voluntary and national interests do feature in the decision-making process.[10]

This process of collaboration between competitors has led to legal action in cases where pre-existing intellectual property is used to define a standard, but in which this IP is not subsequently licensed on equitable terms to all the companies seeking to compete within the jointly agreed standard. Consequently, a letter of assurance is now sought from all participants in these discussions guaranteeing that the owner of any IP will licence the IP for use in further research and will apply non-discriminatory pricing to licenses for commercial use of the IP. This is an attempt to deal with the inevitable vested interests in the standard-setting process. In effect, each company involved agrees to sacrifice the additional profits it would obtain from a privileged IP-position created by the standard in return for benefiting from the higher sales revenue and economies of scale created by the adoption of a shared standard.

The project authorisation request to the IEEE Standards Board to develop the 802.11a standard made on the 16th September 1997 by an employee of Lucent Technologies (the IEEE Working Group Chair and Official Reporter) stated that the proponents were not aware of any patents relevant to this project. There is an explicit question on this in IEEE Standards Board project authorisation forms.[11] According to one of Radiata's founders, who was involved in these discussions as a participant in the IEEE 802.11a design process, the link between CSIRO's patent and the standard was significant but more indirect than tends to be assumed,

> *The standards setting process is a very complex process that isn't played out solely in the standards arena itself. The CSIRO work was very important in influencing the views of the companies driving the standards process and through a small number of invited submissions during the early direction-finding stages of the standards themselves. However, the route was not directly to the IEEE in the early stages but rather through the European standardisation effort, open engineering conferences and a variety of informal means. The level of influence would not be well justified by the official record of submissions, since there was not a policy of making formal submissions. Indeed, I suspect a review of the standards records would find that the CSIRO's work has almost no influence on the standard. The momentum for OFDM came initially from Europe where there were some submissions from CSIRO around 1993/4, before the patent was public, on a standard called Hiperlan 1 that eventually did not choose to use OFDM. We and others thought that OFDM was a clear winner and were amazed when a different scheme was adopted. This standard was a dismal failure and a new standards effort called Hiperlan 2 was started in Europe by the other proponents of OFDM. That work was in parallel with the 802.11 activity but the initiators were many of the same companies as in Europe and the physical layers of the 802.11 and Hiperlan 2 standards were based on the same technical submissions and were ultimately formally aligned. (David Skellern, Personal Communication, 2003).*

If this view is accepted then one implication is that the dissemination of some information on the potential intellectual property prior to the publication of the US patent served a useful purpose in informing the design of the new standard. CSIRO's wireless LAN patent did influence the new standard, but in the diffuse and hard to trace manner that is a characteristic of public good research.

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[9] IEEE stands for the Institute of Electrical and Electronics Engineers. Among other activities the IEEE seeks to define international standards for electrical and electronic systems.

[10] The Minutes of IEEE standards group meetings are publicly available and provide a detailed record of the debates and tactics used to influence how a standard is defined.

[11] IEEE Standards Board project proposals require the Official Reporter to sign a statement in which the statement "I agree to avoid knowingly incorporating in the Standards Publication any copyrighted or proprietary material of another without such other's consent" is included. Thus, the existence of the CSIRO patent was not known of by the Official Reporter at the time the work commenced.

It is worth noting that other well-informed individuals support the view that there is only an indirect connection between CSIRO's wireless LAN patent and the subsequent 802.11a standard. In this view, the patent is based on finding a non-trivial practical solution to wireless LANs based upon parameters set by the laws of physics over radio-wave propagation in this frequency range. Similarly, IEEE 802.11a is also based upon these immutable physical laws. Consequently, the design of IEEE 802.11a is likely to have ended up as it did without CSIRO's patent simply because this is a logical solution. CSIRO took out a provisional patent over a particular approach to meeting these performance parameters prior to IEEE 802.11a being agreed, and licensed this on a non-exclusive basis to Radiata. This gives the organisation property rights over this *particular* engineering solution. The defence of the patent therefore rests upon the particular engineering solution for meeting IEEE 802.11a, it does not make claims over all 802.11a compliant solutions.

Interestingly in this context, a Canadian company Wi-LAN obtained a patent for an ODFM wireless LAN solution prior to CSIRO. Wi-LAN licensed this technology to Phillips and subsequently initiated legal action against Radiata for patent infringement. On the basis of some reports Wi-LAN has in the past sought to claim that all uses of IEEE 802.11a in North America violate their patent.[12] A settlement was subsequently reached by Radiata/Cisco Systems but details are not publicly available. Another company, Atheros Communications Inc. also has a 802.11a product on the market (Atheros also uses CMOS chips and was formed by a Stanford University professor). Subsequently, there has been a high level of corporate activity aimed at forming groups to promote competing implementations of ODFM (notably the versions backed by Wi-LAN and also by Cisco and Broadcom using the CSIRO/Radiata solution).[13] Microsoft also became involved in these maneouvers. Given the tremendous economic potential of wireless LAN solutions and the way in which the US patent system relies upon legal challenges to determine the ownership of IP rather than the existence of a patent per se, future litigation over 802.11a and related solutions is, perhaps, to be expected.[14]

The collaborative work between CSIRO and Macquarie had been directed towards 60GHz mm wave length radio-frequency solutions using Gallium Arsenide (GaAs) technology. The new 5GHz opportunity lowered the bar for the R&D effort, although the initial response was that a GaAs should still be sought. When Radiata was formed they had an existing competitor called RadioLan. RadioLan already had a 10Mbps product on the market. This used a pulse-positioning system that when tested proved to be unreliable. This gave encouragement to Radiata. RadioLan subsequently failed as a business.

The Radiata team had the credibility required to interest external investors, whether these were ICT companies or venture capitalists. Membership of the US-based electronic engineering 'community of practice' was one of the critical elements in the success of Radiata. This network provided the connections between people and the trust that is critical to investors being able to judge the degree of investment risk they face. This is particularly important when attempting to innovate outside of the core of the world ICT market and the hub of corporate venture capital

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12 As reported by Robert Millham and Felix Narhi at Research Capital on January 26th 2001 as reported in an on-line discussion of OFDM and fixed wireless broadband access.

13 The Wi-LAN led group promotes 'wide-band' ODFM and Cisco and Broadcom the 'vector-based' ODFM solution.

14 The US patent system adopts a 'let the courts decide' approach and, as a result, is reported to place less of an emphasis on the process of examining a patent than in some other countries. This approach has important implications for innovative activities because it means that considerable financial resources may have to be deployed to defend a patent both against litigation initiated by others and in order to initiate litigation against those believed to have infringed the patent(s) held. Unless these resources are available the expenditure on obtaining a patent can, in some circumstances, be a waste of money. Patents have several sources of value in industry in addition to protecting IP. They are used to block competitors' innovation paths, force up competitors' R&D costs as they have to 'invent around' patents held by competitors and as assets in negotiations.

finance – the US. One of Radiata's founders had spent the bulk of his career in the US and, significantly, had taken up the option of US Citizenship. As a US citizen he was able to return to the US at any time, particularly important should Radiata fail or need to re-focus its main line of business to contract engineering.

In general, the Radiata team were fully aware of the extent to which potential investors rely upon inter-personal networks to judge the risks they face in making an investment. When reacting to those seeking their investments US venture capitalists ask three key questions: what do you know? who do you know?, and who knows you? Credibility and trust emerge from these inter-personal networks and there is little that can substitute for this means of investor risk reduction. As one of the founders has observed, US providers of risk capital in the ICT industry have over a quarter of a century of experience in learning how best to judge people by getting to know the networks that these people are part of. The fact that each member of the team was perceived, at an individual level, to have a strong track record of success was vital to the venture.

Team members possessing US citizenship also made the company 'American' from the perspective of judging investor risk. This is critical because venture capital firms place a premium on being able to intervene when a company in their investment portfolio is not performing to its potential. The 'tyranny of distance' faced by Australia-based innovators seeking US investment is that this intervention is far more difficult. Consequently, the design team must be a strong positive 'outlier' to the normal risk-reward relationship. Its perceived risk profile must be sufficiently attractive to offset the enhanced risk to the venture capitalist that intervention is less viable if things go wrong. Although Radiata did not, in the end, conclude any deals with venture capital companies these negotiations were carried out. The capacity to intervene at a distance is less of a consideration for 'corporate venture capital' (venture capital investments made by established technology-based corporations who characteristically treat these investments as options for possible future acquisition in order to obtain IP and associated know-how). This, as it turned out, was the type of risk capital obtained by Radiata.

Bringing investment banking experience into the Radiata team also proved critical to reducing the perception of investor risk. This was coupled with the strategic approach of making clear statements over the milestones and other targets that the engineering team intended to hit, and then making every effort to actually meet these targets. This placed Radiata in the useful position of being able to feed this project management information back to potential investors. Again, this deliberate effort to drive-down perceptions of investor risk was critical to the eventual success of the venture. If engineering capabilities are weak then the risk exists that unfeasible targets will be set in order to 'look good' and that the subsequent failure to meet these targets will backfire on the strategy. The strategy only works if the team has the engineering capability to make the strategy work.

One advantage possessed by the Radiata team was that failure to succeed in developing a competitive solution to the IEEE 802.11a challenge would not destroy the business. The option always existed to transform Radiata into a contract engineering company.

Getting the technology right

With hindsight, and in the light of the strenuous efforts made by Radiata to play the investment risk management game effectively, it is easy to put too strong a shine on the success side of things. This would not be accurate as the process was fraught with difficulties. Radiata's engineering challenge may have been tightly focussed upon providing a cost-effective solution to IEEE 802.11a – but they had little idea how to achieve this at the start of the process. As a result, blind alleys were followed in the engineering design process and the risk of failure at an engineering level was present for a considerable time during the innovation process.

Radiata obtained an IR&D Board R&D Start grant of $750,000 in September 1998 on the basis of a contract with the US company M/A-COM. M/A-COM was contracted to develop a radio-based wireless LAN 'radio' chip for Radiata. The R&D Start grant was critical in two respects. Firstly, it allowed them to take on their first employees and to gain some critical mass. Secondly, without this injection of funding they may well have been forced into a deal with a venture capital company. From the founders' perspective this would have almost certainly led to a loss of effective control in terms of tactics and strategy and, as noted above, would have diluted the equity held by the founders and other employees. [15]

A whole year was spent working on the M/A-COM radio contract. This radio was completed by M/A-COM in 1998 – but it never worked effectively. This left Radiata with a major problem. They attempted one interim solution: they asked CSIRO Radiophysics to produce the radio part of a demonstrator chip-based design to operate at 5GHz simply in order to have something to use in Radiata's marketing efforts. The CSIRO radio chip was never used directly by Radiata but it did contribute to forming ideas about the ways to proceed in the design effort.

This is clearly a less than an ideal solution and it illustrates the technical difficulties encountered. CSIRO was able to produce the radio element of the demonstrator for Radiata drawing in part upon the Gallium Arsenide (GaAs) technology being developed by CSIRO at that time as part of radio-astronomy work. Until this point, Radiata's preferred design solution assumed that there would be two chips: a radio chip (via the M/A-COM contract) and a modem chip to be developed by Radiata – reflecting known territory for the Radiata design team. Growing awareness that competing 2.4GHz Bluetooth solutions were moving towards low-cost single chip designs and the failure to develop a separate radio chip forced a change in strategy to meet 802.11a: a single chip solution for a low unit cost. The team had no idea how to achieve this objective but the single chip target helped to focus the next phase of their engineering effort.

Work started on designing two complementary chips in 1999 (a modem and a radio-frequency chip) with the new aim of eventually ending up with a fully integrated design. The low-cost design parameter led to a shift in focus to a CMOS solution rather than GaAs as had previously been assumed. CMOS stands for 'Complimentary Metal Oxide Semiconductor'. These are relatively inexpensive chips to produce and can be sold for as little as US$35 per chip set if they are manufactured in quantities of at least 100,000. Other chips that are able to operate in this frequency range use Gallium Arsenide (as used in CSIRO's demonstator chip), Silicon Germanium (SiGe) or Silicon-on-Insulator (SOI) technologies.[16] All of these are more expensive to produce than CMOS chips. The design objective for Radiata evolved to finding a way of solving a complex set of problems that manifest themselves when a CMOS chip is used at the smallest possible fabrication geometries (0.18μ) and also incorporates a microprocessor operating at 5GHz (small-scale high-frequency problems). This combination leads to operating constraints that must be addressed by developing algorithms and filters able to adjust for these problems. However, the more complex the engineering solution used to counter-act the problem of small-scale high-frequency operation the higher the power consumption, the larger the size of the device and the greater the heat generated. The design therefore had to find 'parsimonious' and elegant ways of filtering signals that did not involve numerous filters. The eventual solution involved using on-chip devices that are rarely integrated into radio-frequency chips due to difficulties in making them perform in a stable manner in such a small-scale high-frequency environment.

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[15] The counter-argument, of equal validity, is that VC involvement brings with it substantial management expertise that can significantly increase the odds of being successful. It is often preferable to have a lower stake in a venture with an increased probability of success that a higher stake in a less promising venture.

[16] This account of the technical challenges faced in designing a CMOS chip to meet IEEE 802.11a draws heavily upon technical information published by Radiata Inc. on the Internet *'Radiata Technology Enables Chip-Level Wireless Engine: A Technology Backgrounder from Radiata Inc*.", no date)

Radiata's engineering design capability

The value of the capability possessed by the Radiata team lay in the ability to design such complex chips without incurring prohibitive design and development costs. Few companies in the world were able to cope with such severe challenges. This challenge has been compared to the equivalent of "writing a million line computer program, running it for the first time and never having a single bug" (Weste, 2002). If the chip does have 'bugs' (design faults) then the chip test fabrication runs required to test whether these design problems had been eliminated would quickly bankrupt the company or delay the time to market. The source of competitive advantage therefore lay in the tacit knowledge required to design error free chips with a minimum of re-design loops.

This is a familiar and highly valuable capability in any engineering environment, where re-design work can amount to by far the majority of all design and development costs. Re-work in design is a major source of cost-escalation in complex systems such as defence platforms (aircraft and complex electronic systems etc) and companies world-wide now seek to develop the capability to minimise the number of design iterations required to reach the target performance levels. In Radiata's case experience, intelligence and imagination allowed the number of design iterations to be minimised.

This experience included the formulation of a set of good practice guidelines for the chip design process based upon pre-cursor chip design work at a company called AUSTEK Microsystems (discussed in the following section). Radiata was able to start its design work with the benefit of this substantial accumulated experience of how best to organise the flow of work required to design a CMOS chip. Although radio-frequency (RF) chip design was a new area to the team they applied the same basic design flow methodology that worked in CMOS design. This generic understanding appears to have been very useful in allowing the team to 'push the envelope' of their CMOS capability into RF chip design. It should also be noted that Radiata hired a top flight RF systems engineer with GaAs experience from his PhD. This expertise in radio architecture in association with his coming up to speed in CMOS design made the radio possible.

The capability of the Radiata team was, and probably still is, an extreme outlier in terms of the probability of success in producing bug free circuits. As a result, the relatively low time and costs required to produce working chips gave them a major competitive advantage. At that time a test run of CMOS chips cost $0.5m (closer to $1m today) and a full re-work of the design would cost as much again and take from three to six months. If the re-work of the design only required smaller modifications to the mask used to produce the chip in order to eliminate a few specific bugs the costs stood in the region of $100k to $200k and would take around one month to complete. Design modifications aimed at enhancing performance in a bug free chip have a similar cost to minor re-designs. To the (limited) extent that there are industry benchmarks for the number of design iterations required to get the design right for this type of chip the norm may stand at around seven iterations of some kind or other – though companies are, not surprisingly, reluctant to reveal these sensitive statistics.

One of the major difficulties faced in carrying out this design work was the cost of state-of-the-art CAD tools that allowed this skill and experience to be used to achieve this high probability of success in meeting design targets. Based upon preparatory work using CAD tools at Macquarie, Radiata negotiated a cost-effective lease-based arrangement with the leading chip design tools company Cadence for the initial phase of CAD work on the understanding that they would acquire these tools when the first chips had been produced. These chip design tools would have cost $1m per annum for a full fee paying customer, whereas the deal with Cadence only cost Radiata $100k for that initial year's design work. Existing networks of contacts allowed this cost-effective deal to be struck, namely an excellent working relationship with Cadence's founder. This relationship with Cadence played an important part in Radiata's eventual success.

As work continued on the two chip design solutions throughout 1999 the risks became more associated with solving the technical challenges encountered as significant progress was made than with working out how to proceed. Radiata began to see that the one-chip approach would work in theory and the task shifted to making it work in practice with a favourable cost profile.

The relationships that evolve between chip fabricators and the companies that use them are a long way from hands-off contracting. As one of Radiata's founders has observed, you have to 'pass muster' with a chip fabricator before they agree to make your chips for you, and this can involve you justifying your business plan to them before they allow you to spend your money with them, (Weste, 2002). Building a close technical relationship with fabricators is an important part of maximising the probability of success in making the chips (a process in which small glitches can have major consequences). The flip side of this close relationship, and the exchange of commercially sensitive information that it involves, is that there is a risk of IP leakage to competitors who also use the chip fabricator. This is one reason why the Commonwealth Government has recently funded a remote chip testing Major National Research Facility (MNRF).

During much of this period Radiata was renting space from CSIRO. The ability to 'trouble-shoot' technical problems in RF design by discussing them with CSIRO researchers and using CSIRO's diagnostic equipment when the company only consisted of some six staff and possessed limited equipment of its own was useful.

As the work aimed at producing a single radio-frequency chip and modem chip solution proceeded, the importance of technological expectations as a basis of competitive advantage started to become apparent. Moore's law is one example of these technological expectations.[17] The literature on the dynamics of technological innovation, drawing upon Thomas Kuhn's work in the philosophy of science refers to these expectations as *technological paradigms* based around sets of *technological trajectories*. Technological paradigms are the mind-sets that define what is, and is not, viewed to be the avenues via which R&D should proceed (Dosi, 1982) Technological trajectories are the technical rules and guidelines used when making engineering trade-offs within a paradigm (such as Moore's Law). These trajectories are important because they allow engineers to factor consensus-based expectations over future performance into R&D and new product/process development plans.

The dominant radio-frequency chip paradigm at the time was associated with GSM chips for mobile phones. These required far higher resolutions in signal processing than the shorter-range LAN 'radio' single-chip solution being pursued by Radiata. The engineering trade-offs are significantly different for GSM and wireless LAN chips. Competitors with considerable GSM chip design capability found it difficult to grasp that it might be possible for Radiata to meet LAN objectives because GSM engineers approached the problem with far higher tolerances. Radiata had set out to develop crude short-range radios on a chip not sophisticated ones. The emphasis was on getting the cost down within more limited range and signal processing parameters than GSM technology requires. In effect, therefore, Radiata was able to gain competitive advantage in the face of very powerful competition simply because it realised that it was operating in a different technological paradigm driven by different market considerations. The statement *"we really admire your spirit but you haven't got a hope in hell of it working"* was made by a respected mobile phone company RF chip engineer on the very day that the first batch of Radiata's single chip 'radios' were delivered for testing. The chips worked as planned. Perspective and appropriate expectations can be critical.

[17] Moore's law asserts that the number of transistors on a microchip will double every two years.

Attracting the attention of potential investors

Frequent business trips were made to the US for meetings throughout Radiata's short lifetime. An interesting relationship had started to develop with Cisco systems – essentially based upon the Radiata engineering team being 'goaded' by Cisco executives to prove that Radiata had a potentially viable technological solution to the IEEE 802.11a challenge. It subsequently became apparent that Cisco had in fact been keeping a close watch on the Australian research since 1992 (Cooper, 2001). The informal dialogue with Cisco eventually involved an invitation from Cisco to meet their expert in this area and to try to convince him of the viability of Radiata's approach.

When Cisco's 'gatekeeper' had been satisfied that the solution was viable, Cisco moved very quickly to take an 11 percent stake in Radiata with an identical stake being taken by the chip fabrication company Broadcom (both stakes involved an investment of $4m and valued Radiata at $36m in Sept 1999).[18] Radiata had been negotiating with Broadcom in parallel to Cisco. One of Radiata's founders was known to Broadcom because he had almost joined them at one point. The Cisco offer came in direct reaction to a comment that Radiata was talking to another large company – which led to the response "*why don't you let Cisco be your VC?".* From Radiata's perspective the negotiations with Cisco and Broadcom were strategic because both possessed complementary capabilities that did not overlap with each other.

The 802.11a compliant chip was completed and demonstrated at a major international exhibition in September 2000. The R-RF5 as it was called, could handle transmission rates of 54 megabits per second, sufficient to send full motion video via the wireless LAN. At that point six large US companies are understood to have made direct bids for Radiata. The names of these bidders have been kept confidential as have the amounts offered. During this period Radiata had been actively seeking more substantial 'Stage Two' funding, and had approached Cisco given that they already held an 11 percent stake in Radiata. Radiata simply did not have the financial resources required to proceed through the next stage of the innovation process. Inventory costs were starting to escalate and setting up a new distribution network started to become a costly and potentially time consuming challenge. Being acquired by a far larger company with complementary assets and the required financial resources would solve these problems.

When Radiata began to seek additional funding the company also initiated discussions with Venture Capital companies in both Australia and the US together with established industry players. The existence of the Cisco and Broadcom stakes is reported to have discouraged Australian VCs, as one VC *commented "We lost them to Cisco there was no way they were going to deal with an Australian VC again after that*".[19] Cisco's bid of AUS$567m (US$296m) was accepted on November 13th 2000 and the deal was finalised in January 2001. When the Cisco bid was accepted Radiata had 53 employees and all held stock in the company. Radiata shares held by staff and management were exchanged for shares in Cisco, which at the time were trading at US$52. Radiata's founders became extremely wealthy overnight in paper terms, although a year later following the 'dot.com meltdown' Cisco shares were valued at US$16 (less than 30 percent of the previous years' value).

It is understood that Cisco did not offer the highest price, Radiata selected the bid that offered the strongest 'fit' with the company's capabilities. One VC who was involved in negotiations with Radiata estimated that a further US$150 million could have been obtained if the highest bid had been accepted. However, time to market was critical given that Radiata's 802.11a solution only had a 12 to 18 month lead over the competition (hence the importance of being able to design the chip with minimal re-design iterations). The good fit with Cisco, which filled a gap in the mammoth corporation as it sought to broaden its product range to include the consumer market was judged to

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[18] Financial figures obtained from Australian Financial Review, 18/11/2000: 'Radiata's success a while coming'.

[19] Australian Financial Review, 18/11/2000 op cit.

provide the commitment and resources necessary to stay ahead of the competition. To put the Radiata deal into context, Cisco made 23 acquisitions in the same year at a combined cost of US$22 billion.[20]

The acquisition of Radiata by Cisco required a re-think of key engineering aspects of the final push to introduce the product into the market. This extended what would otherwise have been a three to six months engineering effort to 12 months in order to produce a fully integrated chip set design compliant with Cisco's demanding performance standards. This involved completely re-designing the analogue to digital converters on the modem chip in order to improve the quality of this transition to the signal. Even with this 'raising of the bar' it was only necessary to go to a second chip set iteration in order to meet the necessary design targets. The modem chip only required minor re-design work following the first iteration and the RF chip worked adequately and only required some minor revisions of the design of the mark used in the manufacturing process in order to improve the signal produced.

The political reaction to Radiata's acquisition by Cisco was mixed. The press reported critical reactions from some State government politicians. For example, Queensland Premier Peter Beattie mentioned the Cisco deal when he spoke at the Australian Venture Capital Association conference in Queensland, observing that "*If that was a one-out deal you would not worry a great deal about it and you would see it a signal of the innovation that there is in Australia…Our problem is that we don't have a hub [of world class locally owned technology companies] here*".[21]

These well-intentioned concerns over the lack of a critical mass of such companies are important. In considering this issue it should also be recognised that Cisco's wireless LAN research hub is now located in Australia. The inter-firm linkages and continuing association with academia, backed by Cisco's substantial resources have helped to launch precisely the sort of a hub that many policy-makers advocate. Furthermore, Radiata's strategy for gaining US investor confidence was based upon presenting Radiata as a US company in the first place. To the extent that this strategy was responsible for the successful introduction of the 802.11a chip into the marketplace then 'selling' an Australian company and an 'Australian' rather than a global technology hub would be less likely to succeed. The realities of the abnormal investment risks that must be taken in order to generate abnormal returns, and knock-on benefits, favour a more international perspective over an 'insular' one.

The Radiata story provides us with some useful lessons on how to obtain better odds in the risky process of turning invention into innovation. At various points in this story pre-existing capabilities in CSIRO and exposure to overseas networks have been identified as playing a helpful role. In particular, Radiata was able to exploit intangible assets that had already been put in place in Australia as part of long-term strategic plans. It is to these intangible assets that we now turn.

[20] Australian Financial Review, 9/2/2001: 'The Big Leap'.
[21] Quoted in Australian Financial Review 18/11/2000 'Beattie adds to chorus of Radiata complaints"

Part Two: Long-term innovation capacity-building in Australia via collaboration between radio-astronomers and electronic engineers

Pushing the scientific research frontier in radio-astronomy involves advancing the technological frontier in radio signal capture and in signal processing. It involves stretching the range of frequencies over which signals can be captured and developing methods for distinguishing between signals and background noise. These represent general challenges for industrial applications from satellite-based communications, mobile phones, through to short-distance applications such as wireless Local Area Networks (LANs). These technological challenges require advances in antenna technology, microchip technology, mathematical applications and other areas.

This close coupling of the technologies used to improve radio-telescope instrumentation capabilities and commercial/defence applications has long been recognised by the radio-astronomy community. This recognition goes beyond simply being receptive to the notion that commercial spin-offs will occur from this R&D work. It extends to a more strategic recognition of the value of building close linkages between the companies that are able to develop and provide critical instrumentation technologies and the R&D, and research training, carried out in order to support radio-astronomy. This results in a system of academic-industry linkages that, since as far back as the 1960s – and possibly before that, has been far more symbiotic than the simplistic 'linear model' of how basic research translates into industrial applications. The scientists and engineers involved in these capacity-building efforts recognised that close links between the radio-astronomy community and electronics companies would also help to build and sustain a competitive electronics industry in Australia.

This track record covers the deliberate creation of an environment for carrying out doctoral research that challenges students to deal with complex projects in which they must deploy leading-edge scientific and analytical skills in order to solve real technological problems. As a result, key figures in the radio-astronomy and radio-physics communities have a long track record of making strategic investments aimed at fostering these symbiotic links with industry. Given the nature and extent of the networks of researchers that have evolved via this symbiotic relationship, the odds of important commercialisation outcomes occurring are, arguably, higher than they are in many other areas of R&D. These long-term strategies were 'open ended' in the sense that they did not have particular end-results in mind, rather they sought to create a better *capacity* to carry out research and innovation in this field.

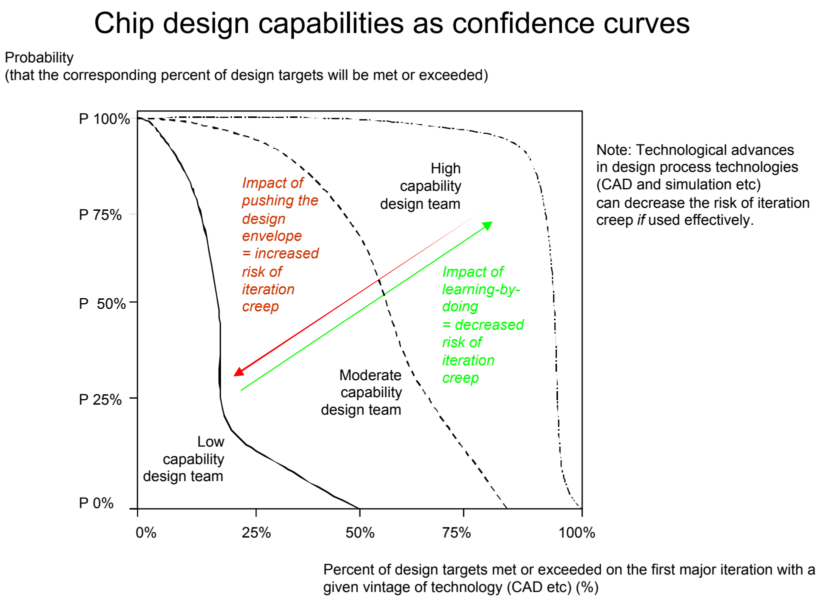
In order to understand the significance of these long-term capacity-building efforts it is useful to place the preceding account of why Radiata's chip design team is now so valuable onto a more formal footing. The capability of Radiata's chip design team was, and probably still is, an 'outlier' in the distribution across competing companies.

The Radiata team's skills were such that they achieved working chips with just two design iterations and some more minor tweaks to the design in order to improve performance. This was achieved for both the CMOS chip components and the RF chip components. This outlier capability has been attributed to the combination of well-proven 'design flow' methodologies for CMOS design based upon substantial experience and exceptionally talented engineers.

From an economic and financial perspective, the value of the intangible asset created by the chip design capability lay in the high probability of success in getting each chip design to work as planned within just a few design iterations. The higher this probability of success the lower the financial exposure to the costs of failing and having to re-run the test chips with consequent increases in time and cost. The higher the probability of meeting or exceeding a large proportion of the design objectives on the first design iteration the lower the time and cost required to complete the design process. This means that the costs of experimental development (the 'D' in R&D) are far lower, and most importantly the speed to market is faster than that of competitors. The combination of skill and experience in chip design and access to state-of-the-art CAD tools creates this capability for 'low D R&D'. Dramatically reducing the time and cost required to complete experimental and full-scale development is particularly important for small economies such as Australia in which there is relatively little scope for economies of scale in R&D funding.

This is illustrated in the following diagram. This diagram represents different chip design capabilities in terms of confidence curves: the different probabilities of meeting or exceeding a given percentage of design targets on the first design iteration. These confidence curves apply to any engineering design process. The better the design team the higher the percentage of the design targets that will be met or exceeded on the first iteration using a given vintage of CAD technology.

'Learning-by-doing' in chip design has the affect of shifting these confidence curves to the right. Pushing the 'design envelope' moves a team's confidence curve to the left because there is a reduced familiarity with the specific technical challenges and a decreased capacity to rely upon using existing solutions. CAD and other simulation technologies that assist designers also play a major role in allowing this curve to shift to the right – provided the skill exists to use these tools effectively. Given the severe cost and time to market penalties of substantial re-design work a high confidence curve can be extraordinarily valuable (particularly if being first into the market brings with it a stream of substantial future commercial advantages).



In the discussion that follows we will show how the 'pre-history' to Radiata shifted the confidence curve to the right to such an extent that it far surpassed the industry norm – thus helping to create Radiata's high intangible asset value. The outcome from the previous decades of investment in creating and enhancing chip design capacity in Australia *is* the relatively high confidence curve – and this remains a potentially important and valuable asset for Australia. This is a product of 'learning-by-doing' generated in part by key people pursuing long-term strategic objectives. There is probably a far wider, book length, story yet to be told about the full nature and extent of this capacity-building activity surrounding, but not limited to, radio-astronomy. This paper simply summarises the key features of these activities and events.

The core of this story is the use of the *Fleurs Synthesis Telescope* (FST) as a basis for doctoral research training that focused upon real-world radio-astronomy challenges. There are also important contributions originating in the US. The creation of Australia's capabilities in chip design is partly the product of international transfers of technology embodied in people with US experience and partly due to a range of spin-offs from building radio-telescopes and associated doctoral training.

A number of leading figures in electronic engineering carried out their doctoral research on the Mills Cross and the FST. The emphasis in their doctoral training in electronic engineering was to expose them to the wide range of engineering challenges generated by a real operating radio-telescope. It also involved teamwork – thereby encouraging the development this important aspect of R&D. This use of the FST as a focus for 'rounded' doctoral research training had its pre-cursor in the work carried out on the Mills Cross radio-telescope at Hoskinstown, NSW (near Canberra). Later on, CSIRO was persuaded to hand over an old field station at Kemp's Creek (to become the FST) to the University of Sydney as a basis for this 'hands-on' PhD work.

The FST doctoral experience has produced cohorts of engineers who subsequently went on to work overseas, and particularly in Europe and the United States. When these engineers subsequently returned to Australia they brought with them considerable expertise and contacts.

CSIRO's Very Large Scale Integration (VLSI) Program was launched when researchers with US experience returned to Australia. This Program was critical to the development of a key element of the Australia Telescope, known as the Correlator Chip. The Australia Telescope's requirements set a substantial challenge for the VLSI Program because it required putting 100,000 transistors on a chip (at that time that was an ambitious goal). This required specialised chips for comparing, synchronising and then multiplying signals from different radio-telescope antennae to be developed. These chips were able to perform multiplications at 1GHz. The Australia Telescope provided the essential user-focus and first customer for this R&D work. The work stimulated by the Australia Telescope enhanced Australia's capacity to design VLSI chips.

The CSIRO VLSI Program was spun off into a company called AUSTEK Microsystems. Austek collaborated with CSIRO Radiophysics researchers in an IR&D Board funded project to produce a 'Fast Fourier Transform' (FFT) chip. The technology was subsequently commercialised by AUSTEK Microsystems. This experience at AUSTEK subsequently contributed to Radiata's success. Interestingly, AUSTEK also supplied the FFT chip initially used by Cochlear. One other spin-off from applying the FFT chip was the formation of Lake DSP. Lake developed the technology used to produce surround sound in headphones, a technology subsequently licensed to Dolby and commonly available on international aircraft.[22]

The final aspect of the 'pre-cursor' capability-building activities to note is the establishment and continuation of CSIRO's work on Gallium Arsenide chip technology when this became unfashionable. In the 1980s CSIRO had accumulated extensive expertise in designing microwave circuits using Gallium Arsenide chips. At the same time, leading US R&D operations such as Bell Labs were understood to be pulling out of research on radio. A decision within this part of CSIRO to continue with the Gallium Arsenide (GaAs) R&D in relation to microwave/radio applications caused some criticism within the organisation as this appeared to be 'against the tide' of global R&D. The advocates of using GaAs technology argued that there was an established technological trajectory of performance improvement associated with Moore's law. When these expectations were factored into the analysis the medium-term potential was promising. At this time Silicon chips could not attain the high frequencies that GaAs technology could.

The decision to continue with the R&D in GaAs and antennas meant that it was possible to draw upon this expertise when contributing to the development of demonstrator microprocessors

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[22] Inevitably, Moore's Law dictated that specialised chips for handling these calculations would become obsolete for consumer applications – a modern PC or aMP3 de-coding chip can easily process information at a sufficient rate to provide this capability.

and also to assist in pre-Radiata demonstrator R&D in this area. CSIRO's GaAs group continued to develop research instrument applications for the Australia Telescope. One spin-off from this R&D was Exicom's 38Ghz technology for linking mobile phone towers. Exicom was eventually taken over by an Israeli company. CSIRO's GaAs group is currently working with US industrial partners on 100Ghz chips. Fabrication cost is less of an issue for research instrument applications because the extent to which costs will reduce with long production runs is irrelevant.[23]

This complex chain of 'pre-cursor' activities was focussed around the dual objectives of improving radio-telescope performance and developing the industrial capacity to provide the technologies necessary to do this. The strategy was long-term and was not explicitly aimed at achieving specific commercial outcomes so much as pursuing a process of 'learning-by-doing' in chip design that would generate a wide range of options for future exploitation. What stands out is: (a) the team-based doctoral training using a real operating radio-telescope as a means of creating the right type of human capital and, (b) the strategic use of new and major upgrades of radio-telescopes further enhance these skills and add experience.

As we move through the 40 odd years over which this story takes place these efforts became more and more focussed upon microchip design as this is where the technological opportunities for pushing the envelope of radio-telescope performance lay. There is a system of 'co-evolution' linking radio-astronomy, telecomminications and microchip design. Radio-astronomy provides the demanding design targets and microchip technology provides the means of meeting these targets. Thus radio-astronomers spend a considerable proportion of their time working closely with electronic engineers on ways of designed more capable chips. This symbiotic relationship at the leading edge of both science and technology provides Australia with a competitive advantage. This is not a 'spin-off' in the familiar sense because it results from the dual objective of fostering *both* scientific and technological capability.

[23] CSIRO's radiophysics R&D continued in other groups. Aside from the Australia Telescope focused R&D, work continued on antennae for microwave landing systems and on the 'feedhorns' for communication antenna systems. Work was also carried out for AusSat in order to allow the communication beam to be shaped to fit Australia's shape thus minimising energy wastage. This group went on to do work for Hughes aerospace.

Part Three: Lessons from the Radiata story

The importance of 'blue sky' basic research in establishing demanding technological requirements for research instruments that, in turn, have wide-spread practical applications

This case study clearly illustrates the ways in which the apparently blue-sky research objectives of radioastronomy stimulate a range of application-oriented technological and engineering R&D. This R&D is aimed at advancing the instruments used to conduct this research. The capabilities of the instruments define what is possible in the research (resolution etc). This type of instrumentation-focused R&D creates substantial spin-off activity. This is primarily because the R&D involves pursuing 'envelope-pushing' performance goals yet also strong overlaps with lower-performance industrial and consumer applications of the technologies.

This type of instrumentation-focused R&D, and the application-oriented research training it requires, is a little mapped but critical pathway for research commercialisation. It often requires, as in this case study, close linkages with existing companies able to develop instrumentation technologies. In this case, the custom chips used in radio astronomy. It is encouraging that Australia's 15 new Major National Research Facilities (MNRF) – which include a radio-astronomy facility and a chip testing facility – have recently agreed to actively pursue technical and managerial cooperation between them. This cooperation covers ICT applications and the geosciences, astronomy, electronic engineering and the biomedical area, (Australian Academy of Science, 2003).

The nature and extent of Australia's inter-personal network-based intangible assets used in innovation

This case study provides an exemplar of how important inter-personal networks are in the innovation process. Consequently, we should aim to ensure that we understand the nature and extent of the networks that Australia currently has – and identify any significant shortcomings or gaps in these networks. This implies that these networks of 'communities of practice' need to be mapped. As in this example, these networks are multi-sectoral but may not always be captured or reflected in formalised associations and relationships. On the basis of this case study these networks also tend to evolve through deliberate strategic planning. Identifying these network champions could be particularly useful.

The strategic management of people's careers in order that they obtain multi-sector experience

These networks are created, in part, by purposeful design. As this case study illustrates with regard to the development of a 'paradigm' for doctoral research training using real radio-telescopes and subsequent career moves that create 'rounded' skills – people's careers and the capability of the network they comprise can benefit from strategic planning. Multi-sector experience: time spent in the research base and in industry can be critical to developing these sophisticated skill sets.

The sustained long-term planning and activities necessary to create these innovation networks

The network-building activities aimed at enhancing innovation capabilities described in this case study are strikingly similar to the mission of the CRC Programme. Yet, they took place without targeted funding and emerged from within the CSIRO and universities. One danger is that the current approach to public sector R&D management may limit the potential for this type of network building by formalising and bureaucratising the process of allocating resources for R&D

and assessing R&D outcomes over relatively short timeframes. In addition, today's shorter-term tenures for senior R&D managers reduces their capacity to establish and to sustain the sort of long-term strategic capacity-building that this case study illustrates. Creating these networks requires budgetary 'slack' and continuity in senior management.

The tactical use of international standard-setting procedures to create market niches

The Radiata story is a clear example of how efforts to define an international standard relating to technology create commercialisation opportunities. International engagement in these multi-lateral standard-setting processes provides Australian innovators with influence over these standards and gives them early warning of any emerging commercial opportunities.

As technologies become more complex and inter-dependent whilst also being influenced by international regulatory regimes, dis-engagement from multi-lateral bodies is likely to have strong opportunity costs for Australia's innovative capacity. Tight regulatory regimes may not appeal to many established companies, who may see these as threats because they lack the technological capacity to develop compliant products and processes. However, these regulatory regimes also provide opportunities for innovation via new companies who champion what can be 'disruptive technologies' (ie technologies that de-value existing corporate IP and hence net worth by doing new things in new ways).

How the 'science-push' ethos meshes with a 'demand-pull' ethos in the face of these risks

Entrepreneurs must characteristically take 'irrational' risks from an investment perspective. One advantage of the 'science and technology-push' ethos is that it provides a frame of reference for taking such risks. The fact that those involved are willing to proceed on the basis of a gut feeling that a solution is technically feasible, even if it does not yet exist provides a counter-balance to the impediment to innovation created by soberly weighing up the investment risks. However, once sufficient progress has been made on a technical level, managing investment risks becomes critical. If this transition comes too early in the process it can impede progress, if it comes too late it can lead to commercially irrational decisions. In Radiata's case, the fixing of a new international standard relating indirectly to an Australian patent played a key role in articulating this link between science/technology push and demand-pull.

How government programs help entrepreneurs to manage investment risks

Undertaking innovation involves taking risks with both the proponents' and other peoples' and organisations' money. The process involves managing these risks and government funding helps to offset these risks – thus making it possible to proceed. When things turn out well, as they did in the Radiata case, luck usually plays a part but this does not imply that risk management is irrelevant. The trick is to consistently seek to invest in obtaining better odds of success. This means that 'success stories' alone are insufficient. We can learn as much, if not more, from failures to innovate particularly when management decision-making contributed to this. One of the most effective strategies for government is to ensure that R&D and commercialisation investment is approached as an investment risk management issue. Grants and subsidies will tend to be most effective when they lead to improved investment risk management capabilities – thus freeing up private investment that would not otherwise be released.

To the extent that networks of the type described in this case study play a critical role in managing these investment risks then the nature and extent of support for these networks becomes a key policy issue. Globalisation provides an opportunity for Australian innovators to offset any risk-inflating disadvantages that stem from innovating in Australia, whilst also allowing any locational advantages, such as cost-effective R&D, to be exploited. International experience and contacts are critical to be able to play the global innovation system. Consequently, government policy should recognise that supporting international engagement and experience and associated flows of people is critical to maximising the benefits and minimising the disadvantages of innovating in Australia compared to an economy like the US.

The significance of these critical intangible assets for mapping our innovation capabilities in terms of their impact upon investment risk management

Radiata provides a useful example of how these networks or communities of practice have, in principle at least, a clear intangible asset value. This asset value is based upon the capacity of these networks to increase the probability of success in achieving risky investment goals. As this case study has demonstrated, use of inter-personal networks both within Australia and at an international level increased the probability of success in the innovation venture. When the risks faced are factored into any valuation of an investment option, the higher the probability of success the higher the expected net present value of that investment proposition. When the probability of success is low the impact of any increase in the likelihood of achieving the objectives sought can have a dramatic impact upon the value of the investment proposition. This network-based aspect of investment risk management is not lost to venture capital companies and other providers of risk capital. Consequently, there is a quantifiable relationship between the nature and extent of these networks and how compelling an investment proposition is.

The long timeframes involved when we consider the capacity-building efforts that precede specific innovative episodes.

Although Radiata was born, grew and acquired by Cisco Systems over a relatively short time-frame (1997 to 2001) this case study has highlighted the importance of the far longer process of developing the capabilities that enabled this particular episode to take place. The development of these capabilities took place over several decades – and was intentionally a long-term strategic process. Consequently, the contemporary focus on research commercialisation in Australia should not neglect the importance of possessing capabilities that may take a long time to develop. These capabilities are developed via the combination of education, research training and on-the-job experience (often overseas). Our options for innovating are partly determined by the capabilities that we currently possess and our options for innovating in the medium to long-term future will be influenced by the decisions we take now over what types of research and research training to fund and how to fund it.

Conclusions

The economist John Maynard Keynes argued that an economy moves out of an equilibrium state mainly because of the (essentially) irrational 'animal spirits' of entrepreneurs. If entrepreneurs soberly calculated the risks of success and weighed these up against the resources they are likely to have to commit at the outset of a venture they would be less likely to proceed. We would all be worse off economically if this 'rational' approach was adopted.

One of the most fascinating aspects of cases such as Radiata's is that the odds of commercial success were, at the outset known to be overwhelmingly low – yet the work still proceeded. The work proceeded via strategies and tactics that increased the odds of success – and this risk-taking eventually paid off. It was probably the expectation that the odds of success could continue to be improved by deliberate actions that drove the risk-taking. Such expectations provide an explanation of how apparently 'irrational' and abnormal risk-taking behaviour can in some circumstances be rational. In Radiata's case it seems clear that the risks faced were less abnormal than they may appear simply because the chip design capabilities were abnormally good, thereby reducing the overall investment risks faced compared to competitors. Radiata's innovation process, in turn, was able to draw upon the intangible assets and intellectual property created by the radio-astronomy and electronic engineering communities in Australia. These intangible assets and intellectual property also helped to increase the probability of success – and in a fundamental sense made this venture possible.

This point can be captured via the concept of learning curve associated with managing investment risks in chip design. In this type of learning curve, cumulative experience leads to a higher probability of reaching target chip performance within given cost and time constraints. In this case study the learning curve has been framed in terms of a confidence curve relating to chip design.

The 'pre-history' of long-term strategic efforts to build-up chip design capability in Australia pushed design capabilities along this learning curve. Without this pre-history the investment risks would have been substantially higher, arguably prohibitively so. Not only did this previous experience improve the odds of success it generated a realistic expectation of future movements along this learning curve – that would further improve the odds of success. It was this dynamic aspect that made it rational to proceed with the attempt at innovation. What may look like very high risks when considered as a snapshot may actually be lower risk when considered as part of a learning curve based process. Consequently, the intangible asset values (why Radiata was acquired for so much and why these informal networks of scientists and engineers are so valuable to Australia) is based not only upon high probabilities of success in the chip design process to date but the expectation of further future improvements in these probabilities relative to those of competitors.

The value of intangible networks of people in increasing the odds of successfully completing the innovation process should not, therefore, be underestimated – even though the networks are hard to identify. They constitute a form of 'human capital' and of 'social capital' (the asset value created by trust and communities of practice). It is therefore necessary to achieve the right balance between informal, intangible networks based upon 'social capital' and the formal legal and organisational structures that are also necessary to conduct research and innovation. These organisational structures are particularly important when there is a need to create and own tangible assets and intellectual property. The Radiata story highlights the benefits of getting this balance about right. On the basis of the available evidence, the CSIRO played a key role in building-up innovative capacity via fostering external network-based relationships and multi-skilled research training. At the time this was done in the broader national interest not for direct commercial gain by the organisation. That said, CSIRO does now have the option to generate revenue from its 802.11a patent and recent press reports indicate that efforts to do this are being put in place.[24]

In radio-astronomy what the science can achieve is dictated by what the technology can do – which in turn is driven by advances in science. Consequently science and technology co-evolve in a symbiotic manner. This means that the path to market and/or adoption is inherent in the formulation of research objectives. R&D of this type aimed at improving scientific instrumentation has the advantage of clear paths to adoption and use because it results in a fully working technology. The main question as regards wider commercial outcomes is the extent to which the *demonstrated* advances in instrumentation technology will diffuse into other markets and industries.

[24] Australian Financial Review 15 October 2003 'Business of science under the microscope'. Bill Pheasant.

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ANNEX A: Technical background

In a wireless Local Area Network (LAN) parts of each signal can be 'knocked out' and partially diminished by the interference caused by these multi-path signals. This leads to a what are known as 'deep fades' – a severe impediment to high data transmission rate communication. In addition, the signals can be contaminated by these reflections leading to errors in associating the different elements of the radio signal with particular symbols. Eliminating this interference in real time was a substantial technological challenge. That said, the market potential for such a technology could be massive *if* a cost-effective and commercially appealing technological solution could be developed.

The impact of the 'multi-path' signal environment on the technologies available in the late 1980s and early 1990s was to limit the rate at which data could be transmitted. The major US corporation Motorola had one solution on the market in the early 1990s (under the trade name 'ALTAIR'). This involved the use of the 18GHz frequency area but could only achieve a (low) data transmission rate of three to six Mbits per second. ALTAIR used a six-element directional antenna system with 6 beams per antenna, giving 36 possible transmission paths. The system checked signal quality periodically and switched to the best quality signal path. This solution, in effect, chose one signal path from within the multi-path system rather than finding a smarter way of living with the multi-path conditions. ALTAIR weighed some 3Kg and consequently fell a long way short of the requirement for a small, light easily portable solution to the multi-path problem. After all, the convenience and flexibility of wireless LAN rested upon being able to operate a computer from wherever it was placed without needing to connect it up to a fixed, or heavy to move, connection point.

Solutions to the multi-path problem based on using a wide spread of the spectrum required too great a spread of bandwidth (around 300 MHz) in order to deliver a slow data-flow rate of 10Mbits per second. Delivering 100 Mbits per second (a far more useful rate) would require 3GHz of bandwidth – and this was too large a chunk to be feasible given competing claims of different uses for the electro-magnetic spectrum. Orthogonal Frequency Division Multiplexing (ODFM) technology using Fast Fourier Transform' (FFT) techniques was seen as one possible solution to this challenge. A technical explanation of ODFM and of the IEEE 802.11a standard that finally emerged as a solution is provided in the following text box.[25]

[25] The IEEE (Institute of Electrical and Electronics Engineers) is a non-profit organisation that plays a major role in electrical and electronic engineering. It has 380,000 individual members in 150 countries and IEEE publications account for 30 percent of global publications in the electrical engineering, computers and control technology. The organisation has drawn up 900 active technical standards and currently has a further 700 under development.

***Orthogonal Frequency Division Multiplexing* and the *IEEE 802.11a* standard**

ODFM works in this context by splitting up a signal into a number of sub-frequencies which are designed not to interfere with each other when they are being transmitted and bounce around a room. The information in the source signal is unpacked and sent in parallel via these different sub-frequencies. If the information contained in a particular sub-frequency is degraded then alternative sources of this information are available via the other sub-frequencies. These sub-frequencies are then combined once they have been received in order to re-assemble the original signal. ODFM is very similar to the approach used in Asymetrical Digital Subscriber Loop (ASDL) combined voice and Internet connections and in digital broadcast television.

Fast Fourier Transformations (FFT) a mathematical technique used to take apart and then re-assemble the signal. One challenge was to develop chips able to carry out these FFT operations fast enough to allow real time transmission. Another major challenge was to integrate the FFT chip with the radio that broadcasts and receives the signal.

In IEEE 802.11a the signal is split into 52 separate sub-carriers using ODFM. Four of these sub-carriers are dedicated to providing information that allows the system to identify and disregard frequency and/or phase shifts caused by bouncing and by interference. This is achieved by generating, transmitting and de-coding a binary test signal. The remaining 48 sub-carriers contain the information to be transmitted in parallel. The various sub-carrier frequencies are separated using a tightly specified range of frequency slots spaced at 0.3125 MHz. IEEE 802.11a operates in the 5GHz band and achieves speeds of 20Mbits per second. The US FCC released 300MHz in three 100mHz sub-bands in the 5GHz region in 1996, in so doing providing a focus for R&D activity. Europe initially adopted a different non-ODFM standard (HIPERLAN 1), later to transform into HIPERLAN 2 which also used ODFM. The battle between these standards, and details of the power that can be delivered in different frequency segments in different countries remains as a potentially contensious issue in developing international standards.

Science has developed sophisticated means of using distortions to electro-magnetic emissions as a source of information about natural processes (e.g. the ‘red shift’ in astronomy), in so doing it has helped to develop the capability to develop technologies that avoid the problems caused by these distortions. IEEE 802.11a is one of many examples of this. The underlying approach to the transmission process based upon dividing a signal up into discrete packets and then re-assembling it is fundamental to the way in which the Internet and defence radio communication systems operate. The mathematical techniques and technologies used to generate such complex yet robust communication systems constitute a public sector research spin-off of phenomenal importance to modern industrial economies.

Fast Fourier Transformations are one of the most important discoveries in applied mathematics of relevance to modern telecommunications. This is because they provide a tractable means of transforming the basis of a signal from a function over *time* to a function of *frequency* and vice-versa. An FFT turns a signal defined in terms of changes in magnitude over time into a signal defined by its distribution of component frequencies (ie cycles). An *inverse FFT* turns a signal from one based upon a set of component frequencies into one based upon changes in magnitude over time.[26]

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[26] The way in which this is achieved is mathematically complex and hard to grasp for non-mathematicians because it involves projecting a mathematical function into a set of complex exponential functions. The trick is that the exponential functions into which the signal is transformed are inherently cyclic (they take the form of a Sine wave). Consequently, periodicity is inherent in the representation of the signal as a set of different cycles. The time dimension is still there, but it relates to each component of the signal rather than to the combined impact of all these components over time.

What an FFT does and why it is important can be conceptualised by imaging a noise that appears to contain no signal (i.e. no discernable pattern) when it is listed to by ear. A Fourier transformed view of the 'noise' would consist not of changes in this overall bundle of frequencies over time, but of a set of different sub-cycles (ie frequencies) – which can themselves be analysed for patterns. Whilst the sound in its combined form (all frequencies merged together) might not appear to contain any information, an analysis of the different cycles that it comprises using FFT may reveal a hidden signal based upon certain frequencies repeating themselves in a regular manner. The powerful technique is also used in time series analysis in economics and finance (looking for patterns in stock market behaviour), and of course in radio-astronomy.

The thinking was that the use of FFT would allow a wireless LAN signal to be broken up into a set of sub-channel frequencies and then re-combined. Most importantly, it could be arranged that the stream of bits (1's and 0's) that coded each symbol being transmitted would take so long to be transmitted relative to the time-delays introduced by reflections within the room that there was little chance of this interference contaminating the signal describing each bit. If contamination and/or signal drop-out did take place something could be done about it because the signal had been de-composed and could be processed in different frequency segments. Each bit could be sent by different sub-channels so if it was affected by interference an alternative signal would be available and various types of error correction procedure could be used.

If the signal is not decomposed into component frequencies using FFT techniques then there is a constraint on the transmission speed. The length of time required to 'spread out' the bits in time, such that this time is far longer than the time-delays caused by all the reflected signals, imposes a severe constraint on the overall speed at which data can be transmitted. In essence, the use of FFT allows parallel broadcasts at different frequencies that enable a sufficiently slow transmission speed to be used at each frequency that it is not disrupted by interference and 'ghosting' from bounced signals. Whilst the basic idea is brilliantly simple (particularly with the benefit of hindsight), its practical application is not.

One key engineering issue was power consumption. If the device(s) developed required too much electrical power then this would limit the scale to which they could be designed and their compatibility with existing computer interfaces (such as credit-card sized the PCMCIA cards that can be slotted into laptop computers and that draw their power from the laptop). It was therefore essential to be able to develop an engineering solution to the problem that minimised power consumption and the heat generated (the heat would have to be dissipated, thus constraining the size of the wireless LAN device and where it could be located).

ANNEX B: List of people involved

The following list of people involved in both Radiata and the previous R&D and capacity-building efforts is not exclusive – it focuses upon the main actors in this story. The names with an '*' are those who had a specific involvement in Radiata and its pre-cursor R&D in the wireless LAN area (including the collaborative research between CSIRO Radiophysics Division and Macquarie University Electronics Department). The other names are of the people who played a role generating the wider capacity to innovate in this area and other areas of electronics. Many other people who played key roles in this story are not included in this list simply for reasons of brevity.

Name	Role(s)
Andrew Adams *	Radio Frequency systems engineer with GaAs experience from his PhD. Hired by Radiata and learned how to link his existing knowledge of RF with expertise in CMOS design acquired at Radiata.
Chris Beare *	Investment banker with a degree in electrical engineering and an MBA from Harvard. Advised Radiata and subsequently became the company's Chairman and Chief Executive.
Chris Christiansen	Electrical engineer who was instrumental in initiating 'hands-on' team-based doctoral training in electronic engineering in Australia using radiotelescopes.
Dennis Cooper	As head of Division supported collaborative work between CSIRO Radiophysics Division and Macquarie University, including the establishment of the joint research centre.
Graham Daniels *	Carried out research on the Fleurs Synthesis Telescope. Joined CSIRO in early 1980s. Named inventor on the CSIRO wireless LAN Patent.
John Deane *	Named inventor on the CSIRO wireless LAN Patent.
Diethelm Ostry *	Named inventor on the CSIRO wireless LAN Patent.
Bob Frater	Electronic engineer with industry experience who became involved in the design of electronic systems at the Mills Cross radiotelescope and subsequently lead electronic systems on the Fleurs Synthesis Telescope and helped to supervise cohorts of graduate students in this field including some of the key players in this story. Headed CSIRO Division of Radiophysics in the 1980s then headed its parent Institute of Physical Sciences. Established Joint Research Centre with Macquarie University and played a role in attracting Neil Weste back to Australia.
Gordon Foyster	Contributed to the Development of good practice guidelines for microprocessor design via work at AUSTEK Microsystems.
Don McLennan *	Appointed US President of Radiata Inc. Played an important role in marketing the company in the US and in managing the overall operation.
Bernard Mills	Astrophysicist who was instrumental in initiating 'hands-on' team-based doctoral training in Australia using operating radiotelescopes.
Craig Mudge	Contributed to building-up Australia's VLSI design capacity following experience in the US. Founded AUSTEK Microsystems.
Steve Simpson *	Joined Radiata after it was formed.
Geoff Smith	Contributed to the Development of good practice guidelines for

	microprocessor design via work at AUSTEK Microsystems.
John O'Sullivan *	Carried out doctoral research on the Fleurs Synthesis Telescope. Joined CSIRO in early 1980s. Named inventor on the CSIRO wireless LAN Patent. Active in building up the collaborative work in this area between CSIRO Radiophysics Division and Macquarie University's Electronics Department.
Terry Percival *	Carried out doctoral research on the Fleurs Synthesis Telescope. Joined CSIRO in early 1980s. Named inventor on the CSIRO wireless LAN Patent. Joint founder of Radiata using personal funds.
David Skellern *	Carried out doctoral research on the Fleurs Synthesis Telescope and then established the communications laboratory at University of Sydney. Following a move to Macquarie University's Electronics Department became centrally involved in collaborative work with CSIRO Radiophysics Division. Joint founder of Radiata using personal funds.
Neil Weste *	Following doctoral research in Australia moved to US and worked at Bell Laboratories and Symbolics and other high-profile companies. Established the US microprocessor design company TLW. Co-authored classic textbook on CMOS design. Joint founder of Radiata using personal funds.

The diagram on the following page (Annex C), taken from Frater (2002), summarises the complex web of pre-cursor activities surrounding radioastronomy R&D that helped to create the capacity for innovation that was exploited by Radiata.

Annex C: How some of the capabilities used by Radiata developed around radioastronomy R&D and its spin-offs