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# Millimeter-Wave Soldier-to-Soldier Communications for Covert Battlefield Operations

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## ABSTRACT

Mobile ad hoc networking of dismounted combat personnel is expected to play an important role in the future of network-centric operations. High-speed, short-range, soldier-to-soldier wireless communications will be required to relay information on situational awareness, tactical instructions, and covert surveillance related data during special operations reconnaissance and other missions. This article presents some of the work commissioned by the U.K. Ministry of Defence to assess the feasibility of using 60 GHz millimeter-wave smart antenna technology to provide covert communications capable of meeting these stringent networking needs. Recent advances in RF front-end technology, alongside physical layer transmission schemes that could be employed in millimeter-wave soldier-mounted radio, are discussed. The introduction of covert communications between soldiers will require the development of a bespoke directive medium access layer. A number of adjustments to the IEEE 802.11 distribution coordination function that will enable directional communications are suggested. The successful implementation of future smart antenna technologies and direction of arrival-based protocols will be highly dependent on thorough knowledge of transmission channel characteristics prior to deployment. A novel approach to simulating dynamic soldier-to-soldier signal propagation using state-of-the-art animation-based technology developed for computer game design is described, and important channel metrics such as root mean square angle and delay spread for a team of four networked infantry soldiers over a range of indoor and outdoor environments is reported.

## INTRODUCTION

The infantry soldier of tomorrow promises to be one of the most technologically advanced modern warfare has ever seen. Around the world, various research programs are currently being conducted, such as the United States' Future

Force Warrior (FFW) and the United Kingdom's Future Infantry Soldier Technology (FIST), with the aim of creating fully integrated combat systems. Alongside vast improvements in protective and weaponry subsystems, another major aspect of this technology will be the ability to provide information superiority at the operational edge of military networks by equipping the dismounted soldier with advanced visual, voice, and data communications. Helmet mounted visors, capable of displaying maps and real-time video from other squad members, ranges of physiological sensors monitoring heart rate, core body temperature, and mobility, arrays of biochemical sensors detecting noxious gasses, as well as a range of night-vision and heat-sensing cameras will all become standard issue. These devices will improve situational awareness, not only for the host, but also for co-located military personnel who will exchange information using mobile ad hoc (wireless) networks (MANETs).

The integration of body-worn wireless systems into the dismounted combat soldier platform will present a unique set of challenges to scientists and engineers alike. Wireless devices will be expected to operate in a range of environments much more diverse than those encountered in civilian applications, yet still maintain an ultrahigh level of performance in terms of reliability and efficiency. From a material perspective, these wireless devices must be compact, lightweight, unobtrusive to soldier movements, and ideally mounted conformal to the body surface. As soldiers may go for days between opportunities for battery recharge or replacement, power saving will be concurrent throughout all layers of the protocol stack. Physical layer (PHY) technologies must be resilient to jamming, able to operate in marginal conditions while using the minimal amount of energy conserving hardware. The medium access control (MAC) layer must also be designed to act in a power-saving bandwidth-efficient manner while maintaining excellent quality of service (QoS). Wireless security will be critical to maintaining a tactical edge as message intercept-

What is fundamental and a key discrimination between soldier-to-soldier MANETs and other MANETs is that the communications are secure and resilient, with a low probability of detection and low probability of intercept, that is, inherently stealthy.

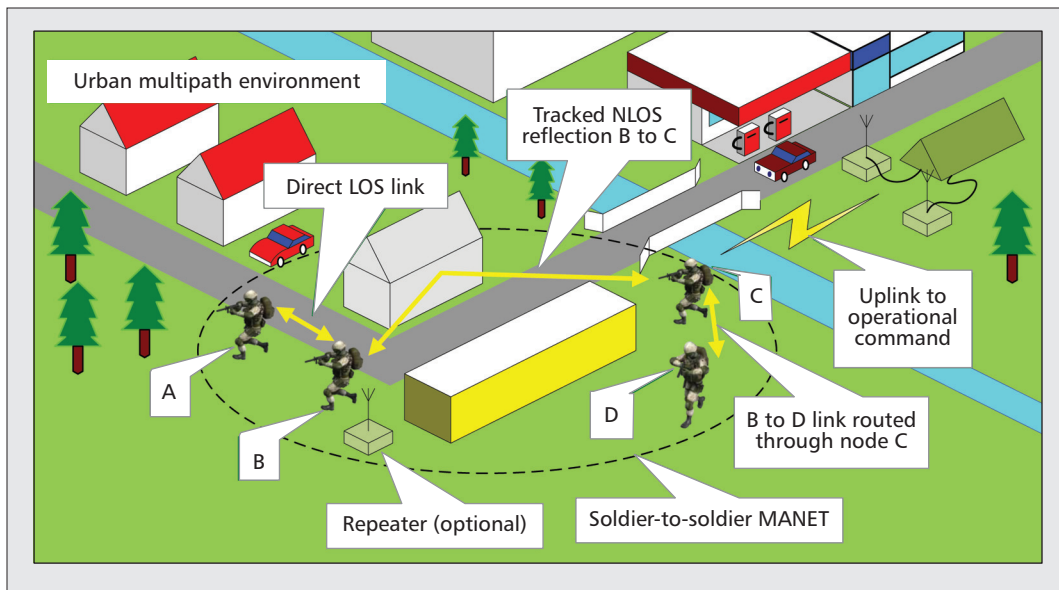


Figure 1. Soldier-to-soldier MANET concept.

tion and decryption could lead to compromise of the mission. When combined with *covert* communications (by covert we mean that signal transmissions remain hidden from the enemy), we have the prospect of achieving secure and robust wireless MANETs while maintaining the *element of surprise*. These are formidable challenges, but may be surmountable using both recent developments in millimeter-wave (mm-wave) transceiver technology [1], and the 5–7 GHz of contiguous bandwidth currently being made available throughout the world in the 60 GHz mm-wave band [2].

In this article we present some of the work undertaken in conjunction with the U.K. Ministry of Defence (MOD) to investigate the feasibility of using mm-wave body-worn antenna arrays to provide covert mobile ad hoc wireless networking for dismounted combat personnel. The objective of this article is twofold. First, we begin by introducing the concept of a soldier-to-soldier MANET and briefly discuss some of the competing air interface technologies that could be used to provide high-speed wireless networking for dismounted combat personnel. We then discuss some of the potential issues at the PHY and MAC layers in relation to the implementation of stealthy, high-data-rate, mm-wave soldier-to-soldier communications. One of the key challenges that remain for military hardware and network designers is the simulation of the wireless transmission channel. A good approximation of channel characteristics is fundamental to testing the performance of newly designed protocols, and understanding the required operating margins for front-end radio design. Therefore, the second section of this article takes a novel approach to the simulation of the wireless transmission channel by exploiting state-of-the-art animation-based technology developed for computer game design to accurately encapsulate the dynamics and mobility of soldier movement in the simulation of signal propagation within soldier-to-soldier MANETs.

## SOLDIER-TO-SOLDIER MANET CONCEPT

The concept of a short-range soldier-to-soldier MANET is illustrated in Fig. 1. In this example a small team of co-located infantry troops are wirelessly networked to facilitate high-speed communications within a cluttered urban warfare environment. As the combat team progress through the environment their communications requirements will be extremely varied, with needs ranging from short message text (e.g., *spoken* by the receiving terminal or displayed on a helmet mounted visor) and peer-to-peer voice (avoiding the need for shouting or hand movements), through to real-time streaming video. What is fundamental, however, and a key discrimination between soldier-to-soldier MANETs and other MANETs, is that the communications are secure and resilient, with a low probability of detection and low probability of intercept (i.e., inherently stealthy). This is especially true for special operations forces where knowledge by enemy forces of increased activity in any region of the radio spectrum may lead to discovery, capture of transmitted data, and/or interference with it. Such intelligence of, or inference of intent from, communications may compromise operations, for example, by revealing the movements of the forces or loss of the element of surprise.

## SHORT-RANGE COVERT AIR INTERFACE TECHNOLOGIES

To achieve optimal network-centric operations, tactical information must be effectively distributed among soldiers while maintaining a low probability of detection and intercept. Ultra-wideband (UWB) is an air interface technology that could supply sufficient band-

Operating ad hoc network communications for dismounted combat personnel at 60 GHz will offer a number of distinct advantages compared to the other competing lower frequency technologies.

width to meet the high data rate requirements of future body-worn military communications systems. UWB radios operate by employing very short duration signal pulses that result in large transmission bandwidths. The U.S. Federal Communications Commission (FCC) defines a UWB device as any device where the fractional bandwidth is in excess of 0.2 of the arithmetic center frequency or greater than 500 MHz, whichever is less [3]. The FCC have granted permission for unlicensed UWB devices to operate in the 3.1–10.6 GHz frequency range with the spectral density emission limit set at  $-41.3$  dBm/MHz to reduce interference with other co-located wireless systems operating within the same spectrum space. The stringent transmit power limitations placed on UWB devices have been chosen so that they minimize the risk of interference to authorized radio services by operating close to the noise floor. This is a feature that many in the military community will find attractive as it introduces a lower probability of detection compared to conventional wireless systems. UWB could provide the dismounted soldier with a maximum data rate of 100 Mb/s [2] for transmitter-receiver separations less than 10 m and as much as 480 Mb/s at very small separation distances (typically less than a few meters). Improvements to operating distance and channel capacity could be realized by raising the spectral density emission limit; however, such a move could prove unpopular as it will lead to increased interference with licensed radio users and remove the stealth mode of operation, leading to easier detection by the enemy.

Compared to UWB, 60 GHz millimeter wave communications will operate in currently under-utilized spectrum space and provide high data rates of up to several gigabits per second for short-range applications [2]. Operating ad hoc network communications for dismounted combat personnel at 60 GHz will offer a number of distinct advantages compared to the other competing lower-frequency technologies. Factors that would generally be considered to hinder traditional radio communications can be exploited to provide the desirable signal propagation characteristics required for short-range military communications. These include increased *covert*ness, high frequency *reuse*, and reduced risk of *interference* (which may be attributed to higher path loss), increased atmospheric oxygen ( $O_2$ ) absorption, and narrow antenna beamwidth. Another important feature of mm-wave frequencies is the *small size* of product that may be achieved. Ultra-low form factor transceiver design will become reality due to the extremely short wavelength ( $\lambda \approx 5$  mm), which will also facilitate the construction of wearable smart antenna arrays capable of electrically steering highly focused beams of electromagnetic energy in chosen directions. To realize the objective of directional mm-wave communications, there are still a number of hurdles at the PHY and MAC layers that need to be overcome, as discussed below.

## MM-WAVE SOLDIER-TO-SOLDIER COMMUNICATIONS: PHY LAYER CHALLENGES

### CHANNEL CHARACTERISTICS

It is widely recognized that the successful development of hardware and wireless networking protocols is highly dependent on a thorough knowledge of transmission channel characteristics relative to deployment. Much of the current research involving mm-wave short-range communications has been carried out considering a range of indoor environments for stationary transmitter and receiver scenarios [4]. Here statistical descriptors of the channel, such as path loss exponent and root mean square (rms) delay spread, are found to be heavily influenced by antenna configuration and the local surroundings. While these studies are useful for the development of indoor wireless networks, any attempt to apply this channel information to the design of mm-wave soldier-to-soldier networks would be inappropriate, especially considering issues such as the scattering of signals from both users and pedestrians, and the inherently dynamic and highly mobile nature of military operations.

At present, very little is known about the characteristics of signal propagation between wearable wireless devices forming a human body-to-body network (BBN). Recent narrow-band studies at 2.45 GHz [5] have shown that signal propagation is dependent on the user's physical characteristics, including mobility, and may be modeled using  $\kappa$ - $\mu$  fading statistics [6]. The effect of human body shadowing on mm-wave wireless links has received some coverage in the literature. In [7] it is reported that human body shadowing can cause attenuations of greater than 20 dB on indoor 60 GHz device-to-device links. Field trials performed for this study to investigate human body shadowing events on indoor point-to-point links have found similar results (attenuations of 20–25 dB), with the greatest shadowing events found to occur when the human body moved in the direct vicinity of a 60 GHz node, blocking line of sight (LOS).

### TRANSMISSION SCHEMES

There are a number of different transmission schemes that could be adopted for soldier-to-soldier communications. These include the single carrier (SC) and orthogonal frequency-division multiplexing (OFDM) schemes currently being investigated by IEEE 802.15 TG3c [8]. OFDM is well known for its ability to mitigate against frequency selective fading due to multipath, by turning the transmission channel into a series of suitably modulated (e.g., quadrature amplitude modulation) orthogonal subcarriers. This has the effect of greatly reducing the complexity of transceiver design through the use of inverse fast Fourier transform (IFFT) and FFT signal processing stages for signal transmission and reception, respectively, and negates the need for intricate wideband equalizers. While OFDM may be resilient to multipath effects, it is prone to a high peak-to-average power ratio (PAPR), phase noise, and carrier offset. High PAPR will be a

particular problem for soldier mounted radios, as it will cause nonlinear distortion and low power efficiency in the power amplifier [2], directly impacting battery life. The complexity of time-domain channel equalization in wideband SC systems is regarded as its main drawback for use in high-data-rate mobile radio channels. However, this challenge can be overcome through the use of frequency domain equalization (FDE). Single carrier systems with FDE (SC-FDE) typically use transmission blocks with a cyclic prefix to prevent interblock interference. Signal recovery at the receiver is then performed through FFT processing with equalization followed by an IFFT stage. SC-FDE will then deliver performance similar to OFDM, with essentially the same overall complexity [9], but because SC modulation uses a single carrier it has the added advantages of lower PAPR and less sensitivity to both phase noise and carrier offset [10].

### RF FRONT-END TECHNOLOGY

The choice of 60 GHz RF front-end technology for soldier mounted radio will introduce a trade-off between performance and cost. Traditionally group III-IV semiconductor technologies such as gallium arsenide and indium phosphide have been used for mm-wave radios. While they offer superior noise characteristics and high gain at mm-wave frequencies, they also suffer from a high cost per unit, poor integration, and low power efficiency. Complementary metal oxide semiconductor (CMOS) technology, on the other hand, will offer lower-cost mass production, improved integration, and increased power efficiency; however, CMOS front-end circuits will also have to address issues in power amplifier output, local oscillator phase noise, and low-noise amplifier design, as discussed in [10]. As a compromise, more recent advances in silicon germanium (SiGe) technology have now made it possible to build miniaturized low-cost mm-wave radio devices, such as the 60 GHz 0.13 mm SiGe BiCMOS double-conversion superhetrodyne receiver and transmitter chipset recently developed by IBM [1]. Here, data rates of up to 630 Mb/s have already been demonstrated for this chipset over a 10 m indoor LOS link using folded-dipole antennas for both transmitter and receiver modules. Based on link budget calculations made in [1], the authors also state that increasing the receiver gain by 12 dBi (e.g., using smart antenna technology) could increase the range by a factor of four assuming free space propagation. Undoubtedly, even greater operating distances may be attained by sacrificing bandwidth and data rates or improving overall system gain. It is clear that multi-gigabit short-range mm-wave devices will be readily available in the short term.

## MM-WAVE SOLDIER-TO-SOLDIER COMMUNICATIONS: MAC LAYER CHALLENGES

### DIRECTIONAL MAC

The successful introduction of covert 60 GHz soldier-to-soldier communications will require the development of a robust and efficient

bespoke directional MAC (DMAC), which will be underpinned by future developments in beamforming hardware, driven by the widespread adoption of standards such as IEEE 802.15.3c and IEEE 802.11-very high throughput (VHT) into the wireless consumer market. At 60 GHz, it is possible to construct a cylindrical antenna array with 32 elements placed a half-wavelength apart, all within a radius of 13 mm. This will permit the development of compact wearable smart antenna technology that uses adaptive beamforming to dynamically adjust the array pattern by altering the amplitude and phase of a feed network. Highly directive narrow-beamwidth interpersonal communications coupled with a 60 GHz operating frequency will help counteract eavesdropping, improve resilience to jamming, and provide a lower probability of detection by enemy forces. However, it will introduce a number of key design challenges at the MAC layer.

Many of the DMACs currently proposed in the literature are directional variations of the single-channel carrier sense multiple access with collision avoidance (CSMA/CA) approach [11,12]. One of the most widely used and well understood CSMA/CA-based protocols is IEEE 802.11. The adaptation of the current IEEE 802.11 MAC for use in directional military systems will require a number of nontrivial adjustments, most notably to the distribution coordination function (DCF). Virtual carrier sensing (VCS), which is performed by listening to directional request to send (DRTS) and directional clear to send (DCTS) exchanges in the local vicinity, should be performed directionally. Nodes that detect a DRTS or DCTS control packet will update a table of directional network allocation vectors (DNAVs) [11]. When the channel is sensed idle, the DNAV will be used to determine whether to defer transmission in a particular direction.

For a node to perform directive VCS (DVCS) and transmit its RTS directionally it must know, or have a good estimate of, the location of its intended receiver. This is probably the single biggest challenge facing directional protocols, but one military wireless systems designers may be well placed to resolve. RTS direction could be obtained from an internal positioning table that is compiled using time and direction of arrival of signal components. In [11] it is suggested that nodes should listen for ongoing transmissions omnidirectionally while in idle mode and during random backoff intervals in contention periods, providing the opportunity to collect time and direction of arrival information as illustrated in Fig. 2. Directional information could also be retrieved during packet reception, using proactive training beacons [12], and from routing information obtained from relayed packets. Digital navigation aids that are often utilized by the military such as GPS (e.g., soldier's digital assistant) and inertial navigation systems may also be used to provide useful information on node locations by appending readouts to the data payload of control packets. However,

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DMACs will be particularly susceptible to many of the common issues associated with wireless networking such as the hidden node problem, deafness, and gain asymmetry. Clearly, these are issues that also need to be carefully considered and warrant further research.

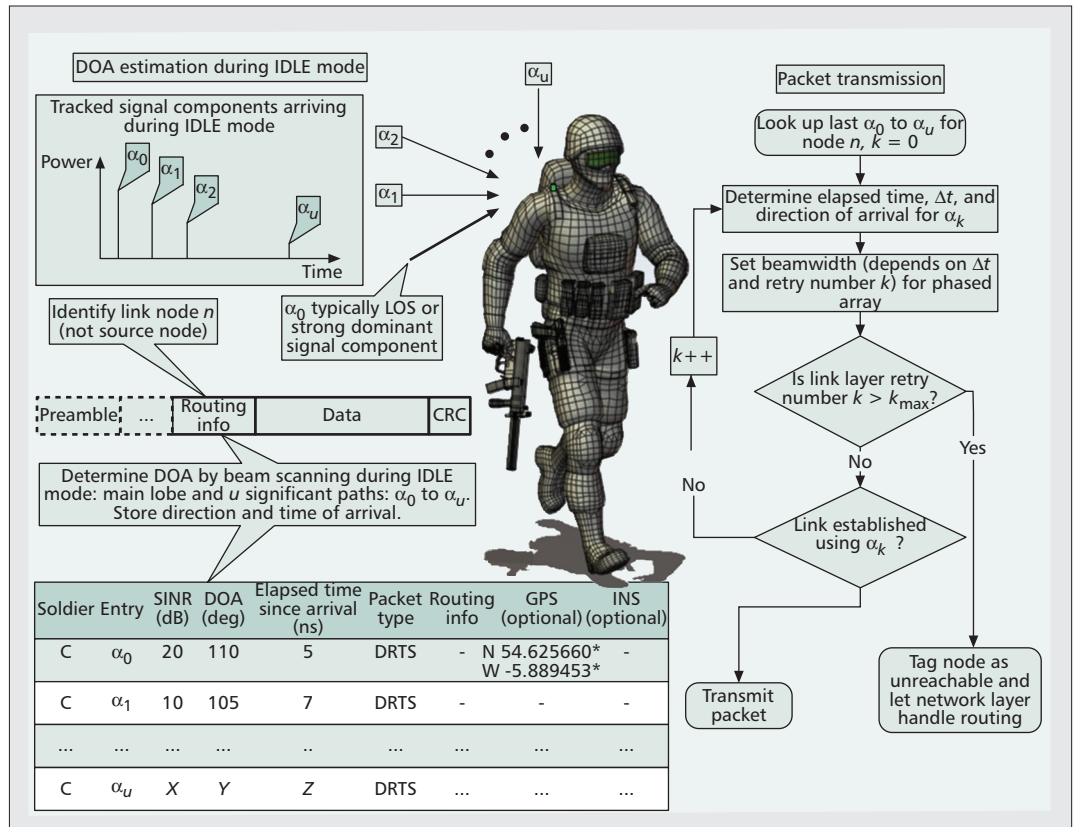


Figure 2. DOA estimation and packet transmission in an mm-wave soldier-to-soldier MANET. Soldier model (height, 1.83 m) generated using Poser 7 animation software.

these methods of direction of arrival (DOA) estimation may not be as effective in indoor environments or when the direct LOS link is obstructed.

To illustrate the operation of a directive MAC layer in a soldier-to-soldier MANET, we return to the scenario depicted in Fig. 1 and assume the soldiers are equipped with radios that make use of mm-wave adaptive beamforming technology, based on a directional derivative of the IEEE 802.11 MAC. As an example, consider single-hop communications between soldiers B and C, and assume that the team has been tracking each other's movements (e.g., using proactive beaconing), and hence have good estimates of their relative locations or DOAs of significant multipath components. If soldier C wishes to initiate communications with soldier B, s/he must transmit a DRTS using the last known good directional entry for soldier B in her/his internal positioning table. All nodes that receive the DRTS transmission (e.g., soldiers A and B who are in idle states) then update their DNAV and internal positioning tables with the incoming signal's DOA and adjust the elapsed time of arrival information. This will include tracking and storing all major multipath components as well as the most significant path as shown in Fig. 2. If soldier B's DNAV table permits transmission in the return direction, the node uses the stored information to beamform in the direction of soldier C and attempts to send a DCTS for a predefined period before timing out. Meanwhile, soldier C also

beamforms in the direction of soldier B waiting for the DCTS. If the DCTS is successfully received, soldier C initiates the directional transmission of data. Throughout this process, all nodes that can hear the exchange continuously update their positioning tables. In the case of soldiers B and C, this will provide the maximum opportunity of re-establishing the link should it unexpectedly go into outage, before abandoning transmission and handing the problem to the network layer for routing, as outlined in the packet transmission flowchart in Fig. 2. This is a relatively simple overview of how directional communications could work in soldier-to-soldier MANETs. However, DMACs will be particularly susceptible to many of the common issues associated with wireless networking such as the hidden node problem, deafness, and gain asymmetry. Clearly, these are issues that also need to be carefully considered and warrant further research.

#### ADAPTIVE POWER CONTROL

Another facility that would further enhance the stealth mode of wireless operation is judicious adaptive power control. Here, radio transmit power is adjusted on a packet-by-packet basis to the minimum level required for operation with a given capacity and error probability. These schemes are often desirable in mobile wireless systems for the purposes of reducing interference and prolonging battery life. In [13] a simple method of implementing power control within the RTS/CTS framework is proposed. This tech-

nique could readily be adapted for use in directional systems by including the beamforming gain within the link power control budget. The DRTS is always transmitted at a predetermined power (e.g., maximum power,  $P_{TX}$ , measured in decibels) and the beamforming gain ( $B_{TX}$ ) used to transmit the DRTS stored in memory. Upon successful DRTS reception, the receiver calculates the difference between the instantaneous received power and its received power threshold, and adds this to its future intended beamforming gain ( $B_{RX}$ ) to calculate the power difference, denoted  $P_d$ . This value is then added to the data payload and transmitted with the DCTS. When the sender node begins transmitting data, it does so using the predetermined power and previous beamforming gain, less the difference (i.e.,  $P_{TX} + B_{TX} - P_d$ ). An optional safety margin ( $P_s$ ), which takes into account fading and node mobility, may also be added to the adjusted output power level chosen by the sender (i.e.,  $P_{TX} + B_{TX} + P_s - P_d$ ). Including adaptive power control in future soldier-to-soldier MANETs will not only aid in reducing interference and battery longevity, but it will also improve the covert nature of communications.

## SIMULATING SOLDIER-TO-SOLDIER SIGNAL PROPAGATION

A range of electromagnetic solver tools are available for simulating signal propagation in wireless channels. Of these, the finite-difference time-domain (FDTD) and ray launching methods are of particular interest. FDTD modeling works by solving Maxwell's equations in the time domain. The FDTD method becomes computationally intractable over large distances at mm-wave frequencies due to the high simulation grid resolution required to achieve an accurate result. Another approach, which is based on geometrical optics (GO) and the uniform theory of diffraction (UTD), is ray launching. In ray launching the transmit antenna launches  $N$  rays over a selected spatial angle. The ray launching algorithm then tracks each ray until it illuminates the area of interest or the power of the ray falls below a preselected threshold level. Because ray launching is based on GO, as the frequency of the carrier increases, the approximation of ray launching to signal propagation improves. A particular strength of using ray launching simulation methods to make channel predictions is that they allow infinite resolution of transmitted and received signal contributions in both time and space. This feature will make them inherently suitable for generating transmission channel information to be used in conjunction with network simulators (OPNET, NS2, etc.), allowing time/direction of arrival based protocols to be rigorously tested. To illustrate the use of ray launching in the simulation of signal propagation in soldier-to-soldier MANETs, we now describe the steps taken to simulate the mm-wave transmission channel between a team of four dismounted combat personnel performing a hypothetical counter-insurgency cordon and sweep operation (this is the fictitious operation depicted in Fig. 3).

## DYNAMIC HUMAN BODY AND ENVIRONMENTAL MODEL GENERATION

A particular problem with achieving realistic transmission channel predictions in scenarios that involve the human body is the encapsulation of movement. One possible solution to this problem is the use of animation software to generate the required dynamics. These programs typically allow the straightforward manipulation of user-created 3D polymesh human figures with the ability to export the animation sequence to a native file format readily interpreted by computer aided design (CAD) software (e.g., drawing exchange format). Figure 2 shows an example snapshot of the soldier model used in this study generated using the walk designer feature of the Poser 7<sup>1</sup> animation software. The lifelike model of the U.S. infantry soldier includes the improved outer tactical vest (IOTV) and lightweight helmet, backpack, pouches, and weaponry. Also shown in Fig. 2 is a single 60 GHz wireless node positioned on the right shoulder which, for simulation purposes, was fitted with a vertically polarized (when the soldier is standing upright) dipole antenna, chosen because of its favorable omnidirectional radiation characteristics in the azimuth. The computer generated environmental model created for this study was designed using the AutoCAD software package from Autodesk.<sup>2</sup> It was based on a small compound as encountered by coalition troops in the Middle East, and is shown in Fig. 3.

## A SIMULATED COUNTER-INSURGENCY CORDON AND SWEEP OPERATION

In this section we present a selection of simulation results from the hypothetical military operation shown in Fig. 3. The simulations followed three distinct stages of a cordon and sweep operation, and modeled bidirectional signal propagation between a squad of four U.S. infantry troops.

### SIMULATOR OPERATION AND SETTINGS

The dynamic soldier-to-soldier transmission channel simulations used a full 3D ray launching algorithm<sup>3</sup> that was set to calculate all reflections, penetrations, and diffractions. A library of purposely written executables were responsible for the amalgamation of the animation sequence and CAD environment model, assignment of dielectric properties to material layers, transmit power, and other related channel simulation properties as well as controlling the automation of the ray launching algorithm. Proprietary software also tracked the changes in antenna orientation caused by soldier movements in 3D vector space. The soldiers were given movements and speeds relative to their role within the operation. The animations were performed at a rate of 50 frames/s, which for the purposes of ray

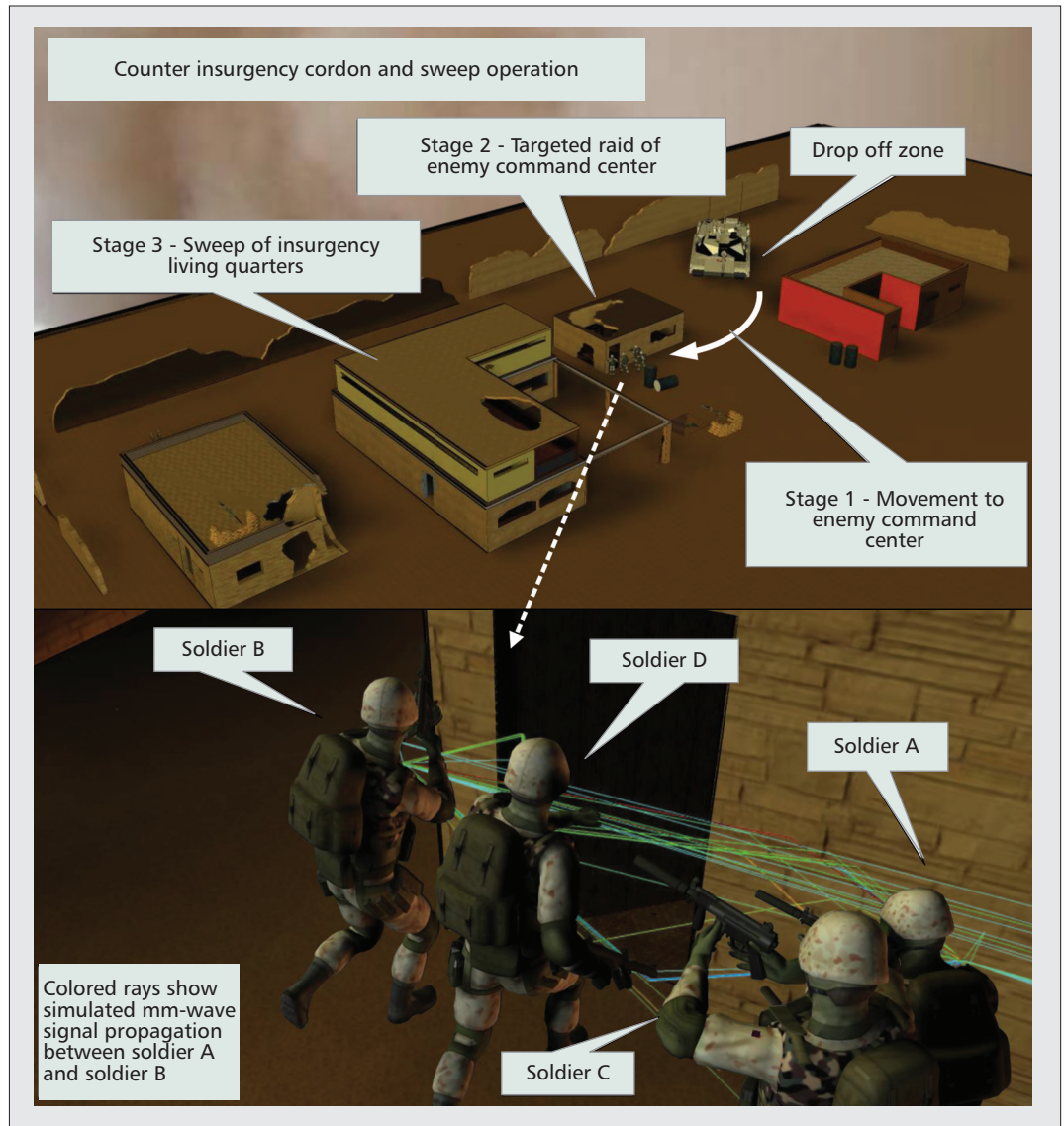
*Including adaptive power control in future soldier-to-soldier MANETs will not only aid in reducing interference and battery longevity, but it will also improve the covert nature of communications.*

<sup>1</sup> <http://my.smithmicro.com/win/poser/index.html>

<sup>2</sup> <http://usa.autodesk.com/>

<sup>3</sup> Algorithm formed as part of RPS software package: [http://www.actix.com/radioplan\\_rps/](http://www.actix.com/radioplan_rps/)

we are particularly interested in the direction of arrival of significant signal components and more importantly their angular distribution in space. This knowledge will be crucial for proving the covert aspect of communications at mm-wave frequencies and the usefulness of beamforming in future soldier-to-soldier MANETs.



**Figure 3.** Upper image: illustration of all three stages of the cordon and sweep operation simulation within a 2258 m<sup>2</sup> Middle Eastern enclosure. Lower image: expanded picture of simulated mm-wave signal propagation between soldiers A and B as the team prepares to raid the enemy command center.

launching simulation is analogous to 50 samples of the mm-wave channel per second. The 60 GHz wireless nodes were set to transmit at a power level of +20 dBm.

#### SIMULATION DESCRIPTION

The overall simulation scenario was designed to encompass a wide range of channel types: indoor, outdoor, and indoor to outdoor. *Stage 1* involved movement of the team from a dropoff zone beside the Abrams M1 tank (Fig. 3) to the entrance of an enemy command center and analyzed outdoor soldier-to-soldier signal propagation. This stage took approximately 5 s to complete. *Stage 2*, duration 4.5 s, investigated both indoor and outdoor-to-indoor signal propagation as three members of the team swept the building, while the remaining soldier maintained guard at the entrance. Finally, *stage 3* lasted for 5.2 s and studied the movement of the team within a large multiroom building structure.

#### DIRECTION OF ARRIVAL

In this study we are particularly interested in the direction of arrival of significant signal components and, more important, their angular distribution in space. This knowledge will be crucial for proving the covert aspect of communications at mm-wave frequencies and the usefulness of beamforming in future soldier-to-soldier MANETs. The key question here: *is the distribution of DOA suitably constricted to provide a stealth mode of operation and warrant the use of beamforming arrays but not too narrow as to limit the system's ability to overcome channel impairments?* The azimuth (or elevation) rms angle spread of the channel impulse response is a measure of the angular dispersiveness of the channel [14]. A transmission channel in which major signal components arrive from significantly different spatial orientations is characterized by a large rms angle spread and vice versa.

The azimuth and elevation rms angle spreads



were calculated at each simulation time step (animation frame) for individual soldier-to-soldier links. Figure 4 summarizes these results by presenting the cumulative distribution functions (CDFs) of rms angle spread over all the simulations (all three stages) and for all bidirectional links. For stage 1, the azimuth rms angle spread had a 90 percent probability of being less than 90°. The corresponding figure for the elevation rms angle spread was lower at 20°, an observation most likely to have been caused by the fact that each of the soldiers were of the same height and were vertically upright for the duration of stage 1. Most important, these results provide solid evidence of the directional characteristics of the outdoor transmission channel and the potential for beamforming arrays to provide a good degree of covertness.

For stage 2, rms angle spread for both azimuth and elevation planes were increased compared to stage 1 (Fig. 4). The increase in rms angle spread, especially elevation, within indoor environments was to be expected, and may be explained by the larger number of multipath components caused by the close proximity of scattering and reflecting objects such as walls, ceilings, and furniture. In stage 3 of the operation, the rms angle spread also increased compared to stage 1. The results from stages 2 and 3 show quite clearly that rms angle spread increases as the soldiers move from a mostly uncluttered LOS outdoor communications scenario to an often obstructed indoor communications one. The rich multipath conditions observed within indoor environments at 60 GHz should generate enough signal components with sufficient angular separation to sustain short-range soldier-to-soldier communications should the main signal path become unexpectedly shadowed or blocked. It is worth noting that while larger rms angle spread within indoor environments may appear detrimental to the proposed stealth mode of operation, mm-wave propagation characteristics will mean that supporting structures should inhibit signal propagation beyond the perimeter boundaries.

## RMS DELAY SPREAD

When high-data-rate wireless systems operate under dispersive channel conditions, they can be subject to intersymbol interference (ISI), which may significantly degrade their performance. The rms delay spread is considered one of the most important parameters for defining the time extent of a time-dispersive radio channel [15] and assessing the potential impact of ISI. When the modulation symbol time is on the order of the rms delay spread, the wireless link is generally considered to be at risk from ISI. Therefore, rms delay spread provides important information for ISI mitigation techniques such as equalizer design. In this work we calculate the rms delay spread from the discrete time power delay profile (PDP), obtained from the complex channel impulse response acquired at each individual simulation time step. Figure 5 shows an example PDP for the wireless link from soldier A to soldier B during stage 1. It can be seen quite clearly that the vast majority of the energy is

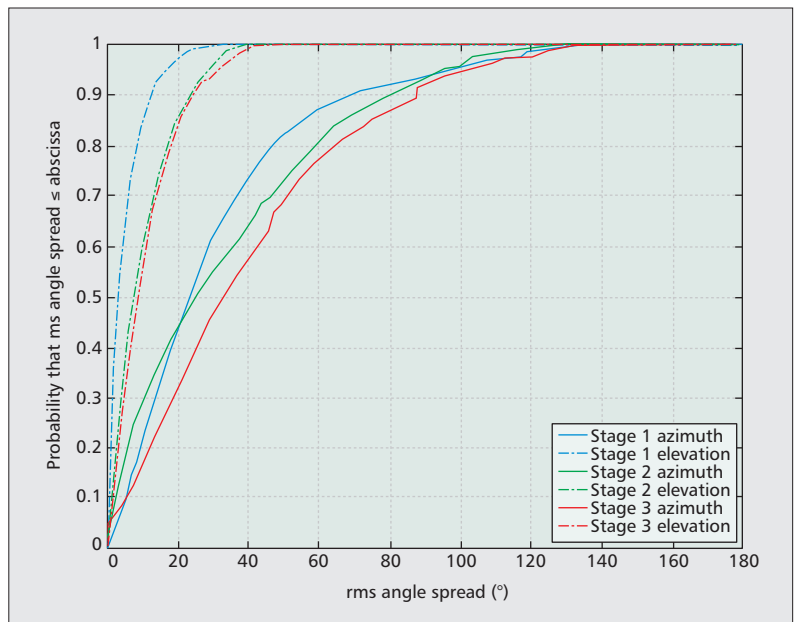


Figure 4. CDFs of rms angle spread over the three stages of simulation for all bidirectional links.

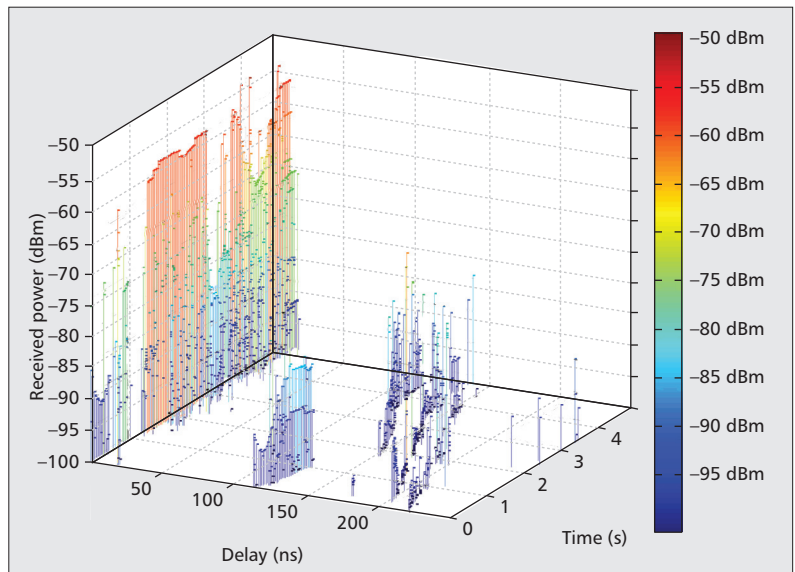


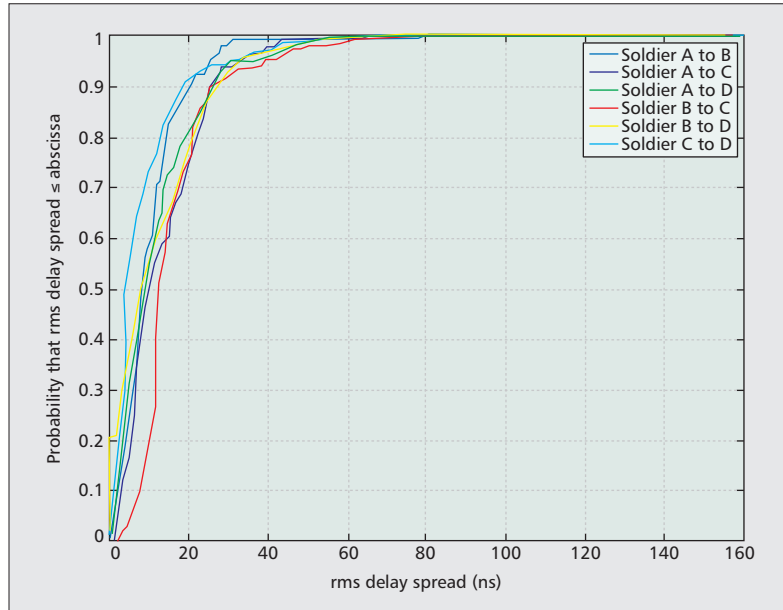
Figure 5. PDPs for wireless link from soldier A to soldier B for the duration of stage 1.

contained within the direct path, which typically arrives within 25 ns. Figure 5 also shows the existence of occasionally significant multipath components that arrive between 100 and 150 ns.

Table 1 provides a summary of the rms delay spread statistics for all bidirectional soldier-to-soldier links for all three stages. In stage 2, where the majority of soldier-to-soldier links were confined within the small dimensions of the enemy command center, the median rms spread was much lower than in stage 1 due to much shorter contributing path lengths. Interestingly, stage 3 had comparable median rms delay spread to Stage 1 despite considering a different environmental scenario. The maximum rms delay spread for stage 3 was 160 ns (Table 1), which,

Stage	Median rms delay spread (ns)	Inter-quartile range of rms delay spread (ns)	Max rms delay spread (ns)	Min rms delay spread (ns)
1	9.1	17.9	162.5	~0.0
2	5.3	6.5	96.1	~0.0
3	10.1	12.4	160.0	~0.0

**Table 1.** Summary statistics for rms delay spread over all three stages.



**Figure 6.** CDFs of all rms delay spreads calculated for each bidirectional link over the duration of Stage 3.

as Fig. 6 indicates, is a relatively rare event. The similar shapes of the rms delay spread CDFs in Fig. 6 also suggest that a similar type of wide-band equalizer may be used for all wireless channels in this scenario. This trend was also repeated for stages 1 and 2, and this in turn means that the complexity of the design of mm-wave transceivers for soldier-centric communications design is reduced.

## CONCLUSIONS

Covert high-speed wireless networks are now a functional requirement of modern infantry and special operations warfare. In this article we have discussed a wide range of issues associated with the application of directive mm-wave systems to meet future soldier-centric networking needs. The concept of a soldier-to-soldier MANET has been introduced and used as an example of a military scenario that could benefit from a stealth mode of operation. To realize covert ad hoc networking, considerable challenges relating to hardware, directive protocols and power control must be addressed. OFDM and SC-FDE transmission schemes coupled with recent advances in SiGe technology look promising for providing high-bandwidth mm-wave soldier mounted radio. The short electromagnetic

wavelength at 60 GHz will allow the construction of compact adaptive beamforming arrays. A directive MAC layer will be required and expected to provide seamless connectivity as well effective management of resources including power control. To this end, possible strategies for creating a directive MAC layer based on the IEEE 802.11 MAC have been described.

A fundamental understanding of the soldier-to-soldier transmission channel will be necessary to rigorously test future protocols and hardware. With the aim of gaining greater insight into signal propagation within soldier-to-soldier transmission channels, we have combined computer generated dynamic human body models and a commercial ray-launching engine to perform channel prediction. It is worth noting that this platform has the ability to simulate dynamic military scenarios beyond soldier-to-soldier signal propagation such as soldier-to-vehicle, including unmanned aerial vehicles (UAVs), and UAV-to-UAV, and is applicable in the frequency range 300 MHz–300 GHz. Simulations performed for this study were based on three distinct stages of a military cordon and sweep operation. For outdoor operations, it was observed that signal DOA was adequately constricted to provide a good degree of covertness. When the team moved indoors, the signal DOA was observed to increase, although the favorable propagation characteristics at mm-wave frequencies mean that signal propagation is likely to be contained within the structure. Delay dispersion was also dependent on local surroundings with the greatest rms delay spreads observed outdoors and within large building structures.

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